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OF THE

IRON AND STEEL INSTITUTE

Vol. CL.

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PREFACE.

THE present volume contains twelve papers, of which seven were issued under the auspices of the Joint Research Committees of the Institute and the British Iron and Steel Federation, that were presented at the Autumn Meeting of the Institute held in London on November 23rd and 24th, 1944. The discussion and correspondence on these papers are also included, together with the authors' replies. At the Meeting a thirteenth paper, published as Special Report No. 30, was also presented. In addition, the discussion on " Blast-Furnace Operation and Problems " (based on one of the papers and Special Report No. 30) and on " Ironmaking at the Appleby-Frodingham Works of the United Steel Companies, Limited " (Special Report No. 30) will be found in this book. During 1944 a booklet on the " Fouling of Ships' Bottoms : Identification of Marine Growths " had been issued, and this is reprinted in the present volume.

The foregoing papers, together with the Minutes of Proceedings of the Meeting and biographical notes on deceased Members, are included in Section I. of this Journal.

Section II. is devoted to a survey of the literature of the manufacture and properties of iron and steel, and kindred subjects, and consists of a collection of abstracts of articles from the Transactions and Proceedings of scientific societies and from the technical press. This section also contains reviews of recent books and bibliographies of literature dealing with the manufacture and properties of iron and steel. The matter included in this Section has already appeared in the *Bulletin of The Iron and Steel Institute,* which is issued monthly.

In front of the title-page are inserted lists of Bibliographies and Special Reports issued by the Institute, together with a list of Translations made available from November 1st, 1944, to April 30th, 1945.

4, GROSVENOR GARDENS,
    LONDON, S.W. 1.
    June 30*th*, 1945.

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ABBREVIATIONS AND SYMBOLS.

Å.	Ångstrom unit(s) $= 1 \times 10^{-10}$ m.	kX.	crystal Ångstrom(s) $= 1000$ Siegbahn X-units.
A.C.	air-cooled; alternating current.	lb.	pound(s).
A.H.	air-hardened.	L.F.	low-frequency.
amp.	ampere(s).	M	molar (solution).
amp.hr.	ampere-hour(s).	m.	metre(s).
approx.	approximately.	m.amp.	milliampere(s).
at.-%	atomic per cent.	max.	maximum.
at.wt.	atomic weight.	mg.	milligramme(s).
atm.	atmosphere(s) (pressure).	min.	minimum; minute(s).
A.W.G.	American wire-gauge.	ml.	millilitre(s).
Bé.	Baumé (scale).	mm.	millimetre(s).
b.h.p.	brake horse-power.	m.m.f.	magnetomotive force.
B. & S.	Brown and Sharpe (gauge).	m.p.	melting point.
B.o.T.	Board of Trade.	mV.	millivolt(s).
b.p.	boiling point.	mμ	millimicron $= 1 \times 10^{-9}$ m. $= 10$ Å.
B.T.U.	Board of Trade unit(s).	N.	normal (solution).
B.Th.U.	British thermal unit(s).	N.T.P.	normal temperature and pressure.
B.W.G.	Birmingham wire-gauge.		
C.	centigrade (scale).	O.H.	open-hearth; oil-hardened.
cal.	calory (calories).	O.Q.	oil-quenched.
c.c.	cubic centimetre(s).	oz.	ounce(s).
c.d.	current density.	p.d.	potential difference.
c.g.s.	centimetre-gramme-second unit(s).	pH	hydrogen-ion concentration.
		p.p.m.	parts per million.
cm.	centimetre(s).	r.p.m.	revolutions per minute.
coeff.	coefficient(s).	sec.	second(s).
conc.	concentrated.	sp.gr.	specific gravity.
const.	constant(s).	sq.	square.
cu.	cubic.	S.W.G.	standard wire-gauge.
cwt.	hundredweight(s).	T.	tempered.
D.C.	direct current.	temp.	temperature.
dia.	diameter.	V.	volt(s).
dil.	dilute.	VA.	volt-ampere(s).
dm.	decimetre(s).	W.	watt(s).
e.m.f.	electromotive force.	Wh.	watt-hour(s).
e.v.	electron volt(s).	W.G.	water-gauge.
F.	Fahrenheit (scale).	W.Q.	water-quenched.
ft.	foot, feet.	wt.	weight.
ft.lb.	foot-pound(s).	wt.-%	weight per cent.
g.	gramme(s).	yd.	yard(s).
gal.	gallon(s).	γ	microgramme(s) $= 1 \times 10^{-6}$ g.
H.F.	high-frequency.	μ	micron(s) $= 1 \times 10^{-6}$ m.
h.p.	horse-power.	$\mu\mu$	1 millionth micron $= 1 \times 10^{-12}$ m. $= 0.01$ Å.
h.p.hr.	horse-power-hour(s).		
hr.	hour(s).	Ω	ohm(s).
in.	inch(es).	$\circ$	degree (arc or temperature).
in.lb.	inch-pound(s).	$'$	minute of arc; foot (feet).
I.S.W.G.	Imperial standard wire-gauge.	$''$	second of arc; inch(es).
		$<$	less than.
K.	absolute temperature (Kelvin scale).	$>$	greater than.
		$\not<$	not less than.
kg.	kilogramme(s).	$\not>$	not greater than.
kg.cal.	kilogramme-calory(-ies).	$\leqq$	equal to or less than.
kg.m.	kilogramme-metre(s).	$\geqq$	equal to or greater than.
km.	kilometre(s).	$\neq$	not equal to.
kV.	kilovolt(s).	$\equiv$	identically equal to.
kVA.	kilovolt-ampere(s).	$\cong$	approximately equal to.
kW.	kilowatt(s).	$\propto$	proportional to.
kWh.	kilowatt-hour(s).		

SECTION I.

MINUTES OF PROCEEDINGS
AND PAPERS OF
THE IRON AND STEEL INSTITUTE.

AUTUMN MEETING
1944

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MINUTES OF PROCEEDINGS

AND

PAPERS AND DISCUSSIONS

AT THE

AUTUMN MEETING IN LONDON, 1944.

THE AUTUMN MEETING OF THE IRON AND STEEL INSTITUTE was held at The Institution of Civil Engineers, Great George Street, London, S.W.1, on Thursday and Friday, November 23 and 24, 1944, the PRESIDENT (Mr. Arthur Dorman) being in the Chair. The sessions on the Thursday started at 11.0 A.M. and 2.45 P.M., and that on the Friday at 10.30 A.M.

At the morning session on Thursday, November 23, the PRESIDENT welcomed all those attending the meeting, and offered a special welcome to the visitors, who, he hoped, would take part in the discussions.

The Minutes of the previous Meeting were taken as read and signed.

OBITUARY.

The PRESIDENT (Mr. Arthur Dorman) : I have to refer to the death of Dr. Thomas Swinden, a Vice-President, and of Sir Maurice H. L. Bell, Bt., C.M.G., an Honorary Vice-President. Dr. Swinden you all knew ; he was a great figure in the steel industry and a charming person, and we shall miss him very much indeed. Sir Maurice Bell may not have been so well known to some of you. His father, Sir Hugh Bell, was a President of the Institute, and Sir Maurice was a very old friend and colleague of mine and a most likeable personality. We all lament their deaths, and I will ask you to stand a few moments in silence.

The Members stood in silence as a tribute of respect.

CHANGES ON THE COUNCIL.

Election of Vice-Presidents and Members of Council.

The PRESIDENT : I am glad to announce that since the last Meeting Mr. J. Mitchell has been elected a Member of Council. At the Council Meeting to-day we elected Mr. J. R. Menzies-Wilson a Vice-President and Sir Arthur Winder, J.P., an Honorary Vice-President. Sir Arthur has retired from active participation in the industry. We also elected Mr. H. H. Burton and Mr. Gerald Steel as Members of Council. Dr. J. E. Hurst, President of the Staffordshire Iron and Steel Institute, has succeeded Mr. B. Thomas as an Honorary Member of Council, and we shall welcome him at Council Meetings.

Vice-Presidents and Members of Council retiring in 1945.

The SECRETARY (Mr. K. Headlam-Morley) announced that, in accordance with Bye-Law No. 10, the following Vice-Presidents and Members of Council would retire in rotation at the Annual General Meeting in 1945 :

Vice-Presidents.—Dr. C. H. Desch, F.R.S., Captain H. Leighton-Davies and Mr. J. S. Hollings.

Members of Council.—Mr. D. R. Lysaght, Mr. N. H. Rollason, Mr. E. J. Fox, Mr. J. Sinclair Kerr and Mr. J. Mitchell.

PRESENTATION OF PAPERS.

A list of the papers included in the programme of the Meeting is given on p. 4 P.

The whole time of the Meeting was devoted to a discussion on Blast-Furnace Operation and Problems, based on the following two papers :

" Ironmaking at the Appleby-Frodingham Works of the United Steel Companies, Limited." By G. D. ELLIOT and the Staffs of the Appleby-Frodingham Ironworks, Scunthorpe, and of the Central Research Department, Stocksbridge (The United Steel Companies, Ltd.).

" Considerations on Blast-Furnace Practice." By T. P. COLCLOUGH.

Four aspects were selected for consideration and were discussed as follows :

Thursday, November 23 :

> *Morning Session :* Fuel Consumption.
> *Afternoon Session :* Furnace Operation and Problems.

Friday, November 24 :

> *Morning Session :* Preparation of the Burden (with special reference to Ore Beneficiation and Sinter). Refractories.

BALLOT FOR THE ELECTION OF MEMBERS AND ASSOCIATES.

Mr. A. VINCENT KEMP (London) and Mr. T. H. STAYMAN (Thornaby-on-Tees) were appointed scrutineers of the ballot for the election of Members and Associates and in due course reported that the following eighty-one Members and fifty-six Associates had been elected :

MEMBERS.

Abraham, William (Plasmarl, Swansea). **Adam,** John Lochhead (Glasgow). **Ashworth,** Wilfrid (Avonmouth). **Barker,** Stanley Melville (Newport, Mon.). **Basant,** Ram Nagar, B.Sc. (Tatanagar, India). **Beattie,** Thomas James (Bengal, India). **Bennett,** *Lieut.* Cyril Christopher (R.E.M.E.). **Bishop,** *Colonel* Alfred Harold, M.C., M.I.Mech.E., M.I.E. (India) (Calcutta, India). **Bosher,** L. (Cheadle Heath). **Braham,** John Edgar, B.Sc.(Eng.), A.C.G.I., M.I.Mech.E. (Norton-on-Tees). **Brooks,** Harold, B.Sc. (Hons., London) (Royal Aircraft Establishment). **Bryant,** Frederick James, Ph.D., B.Sc., A.R.I.C. (Sale, Manchester). **Burkhart,** Francis William (Ministry of Aircraft Production). **Caden,** Robert (Plymouth). **Campbell,** John Graham (London). **Clark,** Norman Arbuthnott, B.Sc.(Eng.) (Sheffield). **Clark,** Norris (Sheffield). **Clarke,** Kenneth William (Edgware). **Claxton,** Cyril Charles (Sheffield). **Crawshaw,** William Henry (Sheffield). **Dewhirst,** Hubert (Stopsley, Luton). **Dixon,** Charles William Satterthwaite, B.Sc. (Hons.) (Stratford-on-Avon). **Draper,** Charles Robert (Hampton Hill). **Drever,** George, B.Sc., Ph.D. (Glasgow). **Efthymiades,** Smar, B.Sc. (Birmingham).

Elliot, William R. (Cleveland, Ohio, U.S.A.). **Elliott,** George (Newport, Mon.). **Evans,** Eric (Connah's Quay, Chester). **Fairhurst,** William, Assoc. Met. (Sheffield) (North Anston, Sheffield). **Fitzjohn,** Arthur Percy, M.I.Mech.E. (Wincobank, Sheffield). **Friedlander,** William, Ing. (Brno), A.M.I.Mech.E. (London). **Gardner,** Frank (Thornton Heath). **Gilbert,** Allen Edwin (Woodford Green). **Gworek,** Jan Mieczyslaw, A.R.T.C. (Glasgow). **Hallas,** Edwin (Grenoside, Sheffield). **Hancock,** Edwin John (Burnpur, Bengal, India). **Iles,** Norman William Maxwell (Iron and Steel Control). **Ineson,** Eric, B.Sc.(Hons.) (Huddersfield). **Jobborn,** Charles Arthur (Middlesbrough). **Jones,** Brinley, M.Met. (Uxbridge). **Kapur,** Uishua Mittra (Lahore, India). **Klopstock,** Hans (London). **Klouman,** Fredrick, M.Inst.C.E. (Edgerton, Huddersfield). **Langrish,** Richard Daniel (Ewell). **LaQue,** Francis Laurence (New York, U.S.A.). **Lee,** Reginald, Assoc.Met. (Sheffield) (Millhouses, Sheffield). **Lewin,** Harold, A.M.I.Mech.E. (Walsall). **Lindsey,** Willard M., B.S. (Chicago, Illinois, U.S.A.). **Lloyd,** Ernest Shuttleworth (Erdington, Birmingham). **Lundquist,** Constans (London). **McDonald,** *Captain* Charles Slater (Technical Staff Captain to Inspector General of Armaments). **MacEwan,** James Urquhart (Montreal, Canada). **Majka,** Stanislaw, Dipl. Ing. (Slough). **Moore,** Norman Clement (Caswell, Towcester). **Moore,** Samuel (Derby). **Morris,** John Richard (Wrexham). **O'Hara,** John James Andrew, A.R.Ae.S., M.J.Inst.E. (Ministry of Aircraft Production). **Peacock,** Arthur Sidney, A.M.I.Mech.E. (London). **Pearson,** Claude Edmund, M.Met. (Sheffield) (Newcastle-upon-Tyne). **Peirce,** Willis M., M.S. (Palmerton, Pa., U.S.A.). **Pellowe,** Ernest Frank, B.Sc., A.R.I.C. (Braintree). **Petteford,** Clive, B.Sc.(Hons.) (Huddersfield). **Pettigrew,** Nicholas (Hornchurch). **Rao,** Nadalike Muthuswamy. B.Sc.(Met.) (Bombay, India). **Roebuck,** Donald William (Burnpur, Bengal, India). **Sharma,** Kedarnath Harnamdas, B.Sc.(Met.) (Burnpur, Bengal, India). **Sharp,** Richard Bruce, A.M.I.Mech.E. (Wellingborough). **Slade,** Arthur Edward (Orpington). **Smith,** Hubert Caldwell (Detroit, Michigan, U.S.A.). **Smithells,** Colin James, D.Sc. (Rugby). **Snyder,** George M. (Pittsburgh, Pa., U.S.A.). **Stalker,** William (Farnborough, Hants.). **Taylor,** Albert Henry (London). **Taylor,** *Captain* James Murray (Technical Staff Captain to Inspector General of Armaments). **Taylor,** Lance Neville (Dronfield, Sheffield). **Taylor,** *Captain* Norman (R.E.M.E.). **Vevers,** Jack (Peterborough). **Walker,** Robert (Swansea). **Ward,** Sidney James Hawthorn (Penn, Wolverhampton). **Whalen,** George (Deepcar, Sheffield). **Willey,** Edward Johnson (Burnpur, Bengal, India).

ASSOCIATES.

Avison, John Maurice (Mirfield). **Baron,** Hedley George (Great Harwood). **Berger,** Peter (Acocks Green, Birmingham). **Bishop,** Derek Arthur (Killay, Swansea). **Brookes,** Peter Eric (Treeton, Rotherham). **Cope,** Lawrence Henry (Walsall). **Crompton,** Herbert (Atherton, Manchester). **Davies,** Trevor Jestyn (Stourport-on-Severn). **Dovey,** Douglas Marshall, M.A. (Cantab.) (Wembley). **Evans,** Gordon Benjamin (Emsworth). **Gardiner,** Leonard Henry (Hounslow). **Glen,** Thomas, B.Sc., A.R.T.C. (Glasgow). **Griffiths,** Norman Jesse (Quinton, Birmingham). **Hall,** Geoffrey Stewart (Tadworth). **Halle,** Charles Edwin (Prestwich). **Harrison,** Leslie, B.Met. (Sheffield) (Stretford, Manchester). **Hobson,** John Douglas, B.Sc., Assoc.Met. (Sheffield) (Millhouses, Sheffield). **Hodgson,** Edward Rennie, B.Sc.(Hons. Met.) (Frizinghall, Bradford). **Hopkin,** Llewellyn Morgan Thomas (Bromley). **Horne,** John Amos (Shipley, Yorkshire). **Horton,** Sidney William (Stocksbridge, Sheffield). **Jones,** Abel (Rhymney). **King,** Thomas Burness (Motherwell). **Lloyd,** Alma (Billesley, Birmingham). **McGavin,** Roy Forrester (Blaydon-on-Tyne). **Mackenzie,** James (Hillsborough, Sheffield). **McLaren,** Peter, M.A., B.Sc. (Glasgow). **Marriott,** Sidney Francis (Cardiff). **Moore,** Donald Charles (Erdington, Birmingham). **Nixon,** John D. (Laleham). **Onaç,** Turgut (Sheffield). **Perks,** Frank (Willenhall). **Preston,** Jack (Hobson, Newcastle-upon-Tyne). **Preusch,** Charles D., M.S.(Met. Eng.) (Orange, New Jersey, U.S.A.). **Rist,** Desmond (Middlesbrough). **Roberts,** Richard Raymond (Southampton). **Rudall,** David Eric (Llanelly). **Samuels,** Leonard Ernest, B.Met.E. (Munitions Supply Laboratories, N.S.W., Australia). **Scott,** Kenneth Percy (London). **Sharp,** Fred (Victoria Park, Manchester). **Smith,** Alastair Ian, B.Sc.(Eng.), A.M.I.E.S. (Glasgow). **Smith,** Eustace Sidney

(Sheffield). **Smith,** Gerald Clive (Cambridge). **Smith,** Peter Warnock (Hobart, Tasmania). **Sommerville,** John, B.Sc., A.R.T.C. (Kilwinning). **Stansfield,** L. (Sheffield). **Stone,** Laurence John (Kensington, Victoria, Australia). **Taylor,** Edwin Albert (Moseley, Birmingham). **Tortise,** Philip Herbert (Hounslow). **Tucker,** Anthony John Philip (Cambridge). **Vaughan,** Geoffrey Raymond (Kings Hill, Wednesbury). **Westland,** Edward George (Farnborough, Hants.). **Wilkinson,** Derek Hilary (Meersbrook, Sheffield). **Williams,** Thomas (Ebbw Vale). **Wood,** Daniel Richard (Cambridge). **Yates,** Francis Sayer (Disley, Stockport).

Complete List of Papers Presented at the Autumn Meeting in London, 1944.

T. P. COLCLOUGH : " Considerations on Blast-Furnace Practice."

W. DAVIES and W. J. REES : " The Bonding Properties of Mixtures of Petroleum Extracts and Linseed Oil and of the Extracts themselves." (Paper No. 9/1944 of the Steel Castings Research Committee (submitted by the Moulding Materials Sub-Committee)).

W. DAVIES and W. J. REES : " The Effect of Grain Shape on the Moulding Properties of Synthetic Moulding Sands." (Paper No. 8/1944 of the Steel Castings Research Committee (submitted by the Moulding Materials Sub-Committee)).

G. D. ELLIOT and the Staffs of the Appleby-Frodingham Ironworks, Scunthorpe, and of the Central Research Department, Stocksbridge (The United Steel Companies, Ltd.) : " Ironmaking at the Appleby-Frodingham Works of The United Steel Companies, Limited." (The Iron and Steel Institute, 1944, Special Report No. 30).

F. FANCUTT and J. C. HUDSON : " The Formulation of Anti-Corrosive Compositions for Ships' Bottoms and Underwater Service on Steel. The Effect of the Pigment and of the Medium." (Paper No. 13/1944 of the Corrosion Committee (submitted by the Marine Corrosion Sub-Committee)).

P. C. FASSOTTE : " Developments in the Design and Use of Side-Blown Converter Plants."

B. GRAY : " The Side Feeding of Steel Castings. A Note on the Influence of the Mechanism of Freezing." (Paper No. 10/1944 of the Steel Castings Research Committee (submitted by the Foundry Practice Sub-Committee)).

R. JACKSON, R. J. SARJANT, J. B. WAGSTAFF, N. R. EYRES, D. R. HARTREE and J. INGHAM : " Variable Heat Flow in Steel." (Paper No. 15/1944 of the Alloy Steels Research Committee (submitted by the Thermal Treatment Sub-Committee)).

F. LÁSZLÓ : " Tessellated Stresses.—Part III."

B. MASON : " The Constitution of Some Basic Open-Hearth Slags."

H. T. PROTHEROE : " The Influence of Melting Conditions on the Physical Properties of Steel Castings." (Paper No. 11/1944 of the Steel Castings Research Committee).

G. C. RICHER : " The Magnetisation of Polycrystalline Iron and Iron-Silicon Alloys."

W. H. J. VERNON, F. WORMWELL and T. J. NURSE : " A Study of the Surface Film on Chromium-Nickel (18/8) Stainless Steel." (Paper No. 15/1944 of the Corrosion Committee).

MARINE CORROSION SUB-COMMITTEE : " Fouling of Ships' Bottoms : Identification of Marine Growths." (Paper No. 14/1944 of the Corrosion Committee (submitted by the Marine Corrosion Sub-Committee)).

THE SIDE FEEDING OF STEEL CASTINGS.*

A NOTE ON THE INFLUENCE OF THE MECHANISM OF FREEZING.

By B. GRAY, B.A.(CANTAB.) (ENGLISH STEEL CORPORATION, LTD., SHEFFIELD).

(Figs. 6 to 18 = Plates I. to IV.)

Paper No. 10/1944 of the Steel Castings Research Committee (submitted by the Foundry Practice Sub-Committee).

SUMMARY.

After agreeing with the view that whirl-gate and atmospheric heads largely depend for their success on the control of the direction of solidification by the temperature gradient, it is suggested that the results are also influenced strongly by factors arising from the mechanism of freezing of the steel. That subject has been much studied in chilled ingots, but very little in steel castings. Four experiments are described with 4-in. square bars cast in various ways. It is pointed out that the rate of increase in wall thickness is less on vertical than on horizontal walls, and different again when the head is applied at the bottom, that the crystalline structures also differ and that two forms of solid result. It is suggested that convection currents play an important part, and that they, in turn, are affected by the size and shape of the casting. The distribution of the secondary segregated material of lower melting point has important effects in feeding. Atmospheric pressure is also important. The mechanism of freezing explains why side heads are less effective with cold steel. The paper concludes with an assessment of the efficiency of various methods of feeding when considered in the light of the experiments described.

Taylor and Rominski (*Transactions of the American Foundrymen's Association*, 1943, vol. 50, Mar., pp. 711–717) described the occurrence of unsoundness in a 2-in. plate cast with an atmospheric head. An explanation, based on differential freezing, is put forward in an Appendix.

A STRIKING feature of steel foundry practice during the past few years has been the development in the side feeding of castings. In Great Britain it has taken the form of the, now, well-known " whirl- gate " head, which depends for its working on the control of the direction of solidification by the temperature gradient. That principle has long been recognised as important, but it has recently been restated and much emphasised by Batty [1] and by Duma and Brinson [2] in America, and there is some danger that it may be considered to be the only factor of importance in the feeding of steel castings.

* Received March 7, 1944. This paper is published by authority of the Steel Castings Research Committee. The views expressed in it are the author's, and are not necessarily endorsed by the Committee as a body.

The " atmospheric " head has been introduced more recently from America and has been fully described in a paper by Taylor and Rominski,[3] which has been reprinted in Britain. It is usually applied in much the same way as the whirl-gate head, but it is " blind " and its height is less. In the ordinary way a " dummy " head often fails, owing to the absence of the atmospheric pressure necessary to force the liquid steel from the head into the casting.

Example A.   Example C.   Example D.

Example B.
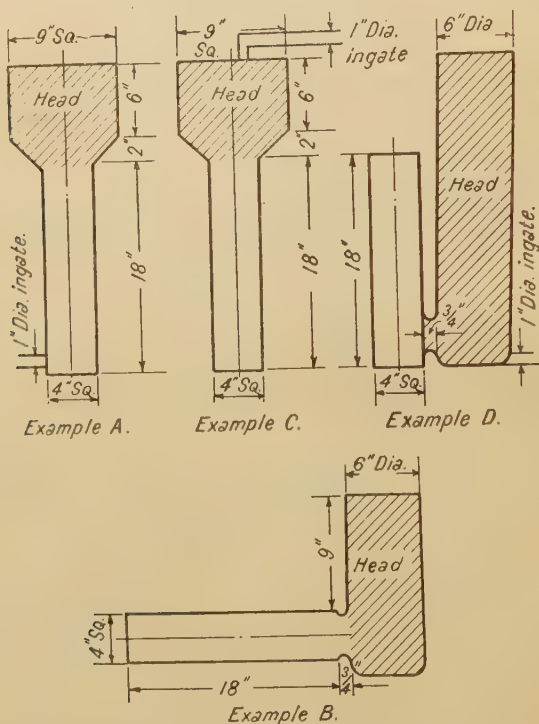
FIG. 1.—Sketch of Casting Designs.

A device in the form of a small core is used to produce a puncture in the first-formed skin at the top of the head, so that atmospheric pressure is admitted to the top surface of the liquid there. As stated, both heads rely primarily on the directional control of freezing by the temperature gradient which they are admirably designed to produce, but, important as that principle is, there are other factors arising from the mechanism of freezing in steel which should not be ignored.

Much has been written on the freezing of steel in chilled ingots, but the subject has been almost entirely neglected in its relation

to the production of steel castings, although information can more easily be obtained from the latter by varying the methods of running and feeding.

For the present investigation, blocks 4 in. $\times$ 4 in. $\times$ 18 in. were made in four different ways (*see* Fig. 1) :

> Example *A*.—Cast vertically with a bottom runner and top head.
> Example *B*.—Cast horizontally with a whirl-gate head at one end.
> Example *C*.—Cast vertically through a top head.
> Example *D*.—Cast vertically with a whirl-gate head near the bottom.

The results obtained from the experiments are reported here and their bearing on the feeding of steel castings is discussed.

SOLIDIFICATION FROM THE MOULD WALL.

It seems to be assumed in most recent publications that steel freezes by a uniform thickening of the wall under all circumstances, except in so far as the process is modified by variations in the thermal capacity and conductivity of the moulding material and by the shape of the mould. That the assumption is not true is proved by Figs. 6 and 7. Fig. 6 is a sulphur print of casting *A* (4 in. $\times$ 4 in. $\times$ 18 in.) with a large head bottom-run and made vertically. After $10\frac{1}{2}$ min. the bottom box was dropped off and $7\frac{1}{2}$ in. of the casting were cut off with an oxygen lance. A small amount of liquid drained out, but the casting was solid, except for the small unusual type of cavities shown. The thickness of the wall of the casting, undisturbed by the draining operation, varies and is everywhere less than 1 in., and it is evident that there was much loose solid matter in the interior, with only a small amount of liquid. Some of the liquid had come down from the top of the head, as is shown by the fact that the dark patch on the sulphur print, indicating sulphur segregation, is unusually small there.

Fig. 7, (*a*) and (*b*), is a photograph of two specimens of example *B*, drained after $8\frac{1}{2}$ and $4\frac{1}{2}$ min., respectively, by burning a hole in the bottom of the head. They are similar castings to *A*, but were made horizontally with the whirl-gate head, and a few drops only were obtained from the centre-line of *B*2. In this casting, freezing had taken place almost entirely by growth from the walls of the casting, at a rate that agrees fairly closely with that obtained by mathematical calculation, which is of the order of 0·2 in. per min.

Thermocouples in similar castings showed that example *A* froze completely in 17 min. and example *B* in 12 min., a difference caused by the method of running. In example *B*, heat was absorbed from the steel in the head before it entered the casting, while in *A* the steel all passed through the casting and would lose

heat before it reached the head. The rate of freezing of the wall in A was approximately 0·095 in. per min. and in B 0·23 in. per min., a difference that is too great to be attributed to the difference in temperature alone.

Types of Crystallisation.

As will be seen from the macroprints, widely different kinds of crystalline structure are obtained according to the conditions under which the steel freezes; for instance, the analyses of the steel in the top and bottom halves of example B (Fig. 8), if not identical, were similar, but the form of crystallisation is utterly different. The central core showing dark on the sulphur print, on the other hand, would contain considerably more carbon and sulphur. The study of the different crystals in steel and their distribution is a difficult and contentious subject with which it is not proposed to deal here, but from a practical point of view it can be assumed that in ordinary steel there are always these two forms of solid :

Primary.—The bulk of the solid, having varying structure, but conforming closely to the analysis obtained from a spoon sample, though with increasing impurity content as solidification proceeds.

Secondary.—A highly segregated solution, containing considerably more sulphur and carbon than the spoon sample, which appears to freeze almost simultaneously over a considerable area.

In example A most of the secondary solidification occurred in the head, where it appears as a brown patch in the sulphur print (Fig. 9). The remainder was contained in the V-threads in the upper centre of the casting and in minute particles well distributed through the remainder of the section. It should be noted that the bottom third of the casting was exceptionally free from segregate and, containing on the whole the purest steel, froze at the highest temperature.

As it is, the casting contained only minute defects on the centre-line, but, if the highest-freezing-point material had not collected at the bottom, it is clear that the casting must have been unsound. That is to say, if such a casting really froze only from the mould face inwards at a rate proportional to the dissipation of heat, no casting of uniform section bottom-run with a top head could possibly be sound, as it would freeze more slowly at the bottom, where the sand has been heated by the incoming metal.

When the same casting was made vertically and run through a top head (example C, Fig. 10), the distribution of the segregate was similar to that in example A, but the columnar wall was considerably thicker at the bottom end of the casting and the V-segregates, confined to the upper half, were less pronounced and flatter.

On the other hand, in example B, with the casting made on the

flat, freezing was almost entirely inwards from the walls, and when the solidified matter met at the centre the secondary residue was squeezed towards the head in a passage tapered by the temperature gradient induced by the method of running. There it was blocked by the material in the head, which was pure and of high melting point and therefore froze first, although it was at a higher temperature. As a result there is a slight unsoundness due to the freezing and contraction of the secondary material later.

Example *D*, cast vertically with a whirl-gate head (Figs. 12 and 14), is different again, the crystal structure presenting a confused appearance, and not a marked pattern about the centre-line as in the other cases. The columnar wall is very thin, and the sulphur print indicates that the segregate is uniformly distributed, except for a faint streak running from the centre-line in a curve towards the neck.

CONVECTION CURRENTS.

Reviewing these four samples, one is driven to the conclusion that the differences in the behaviour of the steel in freezing are influenced by convection currents in the liquid.

In example *B* these currents were almost entirely absent, owing to the small vertical height and the fairly even temperature gradient, while in example *C* they were not powerful, owing to the steel in the bottom of the mould having entered first and therefore being the coolest. In example *A* they were more powerful, because, owing to the method of running, there was hot steel in the bottom when casting was completed, the hot steel rising to the top as soon as the turbulence due to running ceased.

In example *D* convection currents were relatively strong, and the steel entered hot at the bottom, which was also kept warm by the connection with the head, while the top of the casting was coolest when casting was completed. Immersion thermocouples, placed on the centre-line of a similar casting, showed that the position was reversed immediately afterwards, and the steel nearer the top became the hotter and remained so till freezing was almost completed. Owing to the convection currents, the steel near the walls was relatively warmer, the wall growth was slower and most of the crystal growth took place from nuclei in the liquid. Final solidification was from the top downwards, however, as convection currents ceased in the later stages and heat dissipation was more rapid from the top.

Convection currents are also of importance in side heads, and here the advantage lies with the atmospheric type. It is shorter in comparison with its bulk than the whirl-gate head, and therefore convection currents are less pronounced. Also, the top surface is kept hot, because it is insulated by sand from the atmosphere, and later, as soon as the level of the liquid has fallen, there is an insulating layer of gas or air to prevent still further the loss of heat

from the top surface. Thus, the tendency for the hot steel at the bottom to be replaced by that which has been cooled down at the surface is much reduced, and the temperature is kept up opposite the entrance to the casting, where it is required. Incidentally, the effectiveness of the various feeding materials used on the top surfaces of the liquid in open heads is at least partly dependent on the same principle, and they tend to keep the liquid hot at the base of the head near the casting, as well as at the surface.

The Effect of the Size of the Section on Crystallisation.

Steel in freezing does not behave in the above way in castings with a thickness less than about 3 in., because after the preliminary growth of the columnar wall is finished there is no time for marked segregation to take place or room for convection currents to occur. The secondary crystallisation, therefore, is widely dispersed along the whole of the centre of freezing, and is associated with slight unsoundness. For that reason it has been found impossible to cast thin plates free from at least microscopic unsoundness by ordinary methods of feeding.

Taylor and Rominski [4] have described the unsoundness produced in the bottom half of a 2-in. plate cast with an atmospheric head applied to the middle of the plate. In an Appendix an explanation, based on differential freezing, is put forward.

Factors Controlling Feeding.

It is thus evident that controlled direction of solidification brought about by the temperature gradient is by no means the only factor in feeding the steel casting, and that for some castings the normal method of bottom-running with the top head is satisfactory, even in theory, in spite of the temperature gradient being in the wrong direction. The full benefit of the favourable temperature gradient with the whirl-gate head is not obtained, because high-melting-point material collects at the bottom of the head and may freeze earlier than the low-melting-point material in the casting if the temperature difference is not sufficient. Then, again, the segregated material can escape into the head more easily with a top head, as it tends to rise naturally, owing to its lower specific gravity. In doing so, it enriches the steel in the head and lowers its freezing point below that of the casting, which, of course, helps feeding. It is only in a top-run casting with a top head that the temperature gradients and the relative freezing points of the part of the casting last to freeze and of the material fed to it are all favourable.

The Secondary Liquid.

The amount of secondary material collecting near the head in a casting, such as example B, will depend partly on the composition

of the steel (with high carbon and sulphur it will be greater), and partly on the amount of steel that the head is feeding. Thus, the secondary material in example B is the residue from the whole of the steel in the casting. If the casting had been 12 in. long instead of 18 in. there would have been little or no unsoundness, and most of the secondary material would have escaped into the head.

ATMOSPHERIC PRESSURE.

Another source of danger in the use of the whirl-gate head, and even more of the atmospheric head, may lie in the strength of the columnar wall at the top of the casting. This is well illustrated by a repeat of example D, which was made in a skin-dried mould insufficiently dried at the top, causing blow-holes, as shown in Fig. 11. These blow-holes constituted a puncture of the skin similar to that produced by the core in the atmospheric head, and it seems probable that the gas present set up sufficient pressure to overcome for a time the ferrostatic pressure from the head, and feeding took place from that point instead of from the head. It is difficult to picture exactly what happened, as it is hardly conceivable that there was sufficient gas pressure to overcome the pressure from the
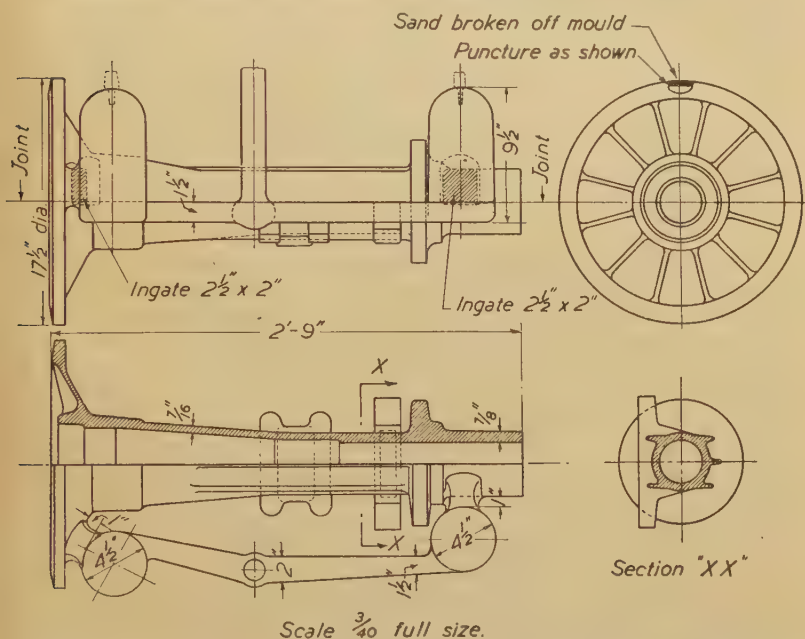

FIG. 2.—Sketch of Back-Axle Flange. Cavity caused by sand. Weight of casting : 1 cwt. 2 qr.; weight of heads and runners : 1 cwt. 6 lb. = 70%.

head throughout the period of freezing. The most likely explanation seems to be that the greater part of the casting inside the columnar wall was a mixture of liquid and solid like the contents of a cocktail-shaker, all freezing simultaneously, with some rather highly segregated liquid at the top. By that time, the level of the liquid in the head may have fallen to that in the casting and frozen over owing to contact with the atmosphere. At the same time the gas contained in the top of the casting would thermally insulate the surface of the liquid there and prevent it from freezing over, thus maintaining atmospheric pressure. Under those conditions material would be sucked from the casting into the head, with the kind of result shown.

A piece of broken mould floating up on the steel can have the same effect, and one such case is illustrated in Fig. 2.

Application to Whirl-Gate Heads.

It is common experience with the whirl-gate head that failures are more likely to occur when the steel is cold; example *B* (Fig. 8) is a typical case, since it was cast very cold at the end of the heat, and is actually almost short-run on one corner, where there is a deep cold-lap. It seems probable that small crystals of high-melting-point material had already formed in the liquid while the casting was still being run, and froze rapidly on contact with the sand. With solidification starting at such an early stage, there was no time for the lower rate of dissipation of heat in the head to have its full effect in retarding solidification there, as compared with the cooling rate in the casting. This casting was the least sound of several made in the same way.

The Design of the Neck.

The heavy macro-etching of example *B*, illustrated in Fig. 8, has much exaggerated the appearance of unsoundness, but, while the casting would be considered sufficiently. well fed for most purposes, it must be admitted that it is not entirely satisfactory. This raises the question of the design of the neck connecting the head and casting. A thin and relatively deep angle of sand is necessary to obtain the full benefit of the reduced neck, and therefore, when the head is applied to a face of the casting of dimensions similar to those of the section to be fed (as here), it is not safe to make any reduction at all. In the same way it is difficult to apply the whirl-gate head to a round bar or tube, because the angle of sand is not sufficiently thin to maintain the temperature of the neck. On the other hand, where a really thin layer of sand can be employed, castings can be fed through surprisingly small necks, no larger than runners and which can be removed from the head with a sledge-hammer. The ring casting illustrated (Figs. 3 and 13) is a sample which proved entirely satisfactory.
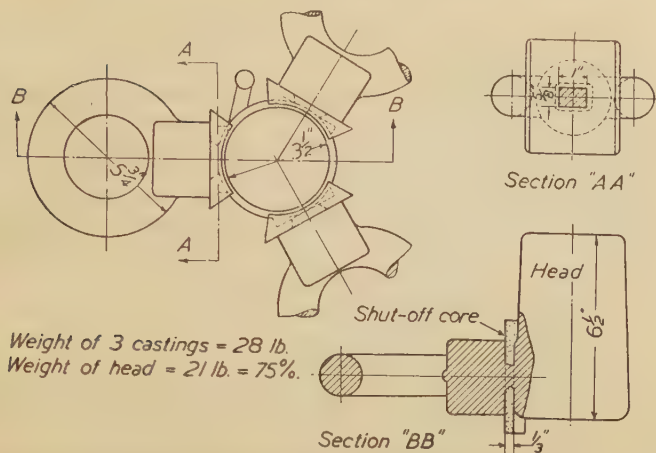
Section "AA"

Head

Shut-off core

Weight of 3 castings = 28 lb.
Weight of head = 21 lb. = 75%.

Section "BB"

FIG. 3.—Moulding Drawing for Castings to be fed through Small Runners.

THE CHOICE OF THE TYPE OF HEAD.

Examination of all the foregoing observations suggests that generalised statements of practical application in the foundry can be made regarding the type of head giving good results in any particular case.   These are very briefly set out below :

(1) Atmospheric pressure and not gravity is the effective motive force in the feeding of all castings.

(2) Top-running through the head is effective in sections greater than 3 in., particularly when the shape of the mould is favourable (*see* Fig. 4 (*a*)).

(3) Bottom-running with top heads is satisfactory under the same conditions (*see* Fig. 4 (*b*)).

(4) Top heads are not efficient in sections less than 3 in. thick.

(5) Top heads are not efficient in horizontal feeding (*see* Fig. 4 (*c*)).

(a)   (b)   (c)   (d)   (e)   (f)
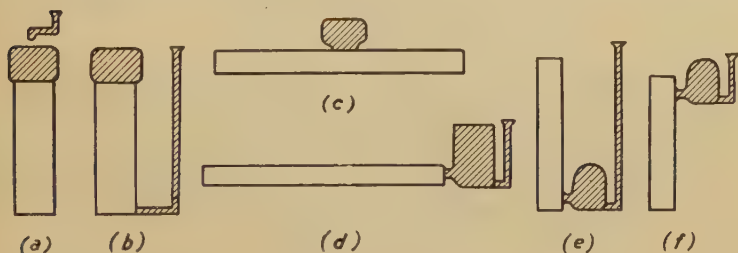
FIG. 4.—Various Types of Feeder Heads.

(6) Side heads give a greater depth of solid wall in horizontal feeding and are therefore to be preferred in certain cases (*see* Fig. 4 (*d*)).

(7) Side heads are effective to a considerable horizontal distance from the head.

(8) Side heads in horizontal feeding are liable to leave slight axial unsoundness in the casting.

(9) Side heads applied to the bottom of a casting give the best results in sections under 3 in. thick and are quite effective for thicker sections when applied so that the head keeps the bottom of the casting hot by conduction (*see* Fig. 4 (*e*)).

(10) Side heads are not so effective when applied to the top of a casting (*see* Fig. 4 (*f*)).

(11) The conduction of heat from the head to the casting during freezing is important and is controlled by the size of the head and the design of the connection with the casting.

In the foregoing estimation the size of the neck is ignored, as, from the feeding point of view, a reduction there can equally well be applied to top heads. In practice it is not so convenient, but that and other practical considerations affecting the cost of production are not discussed here.

The number and variety of the examples and the observations of temperature, chemical analysis, &c., made have been much restricted in this investigation by the superior claims of production in both the foundry and the research department. These limitations are still so serious as to make it impossible to undertake, in the immediate future, an adequate research on the points of interest disclosed, and it has been arranged that further co-operative investigation shall be carried out under the auspices of the Steel Castings Research Committee.

It is gratifying to the author that the Committee have undertaken this work, and he is personally indebted to the Chairman and other members for advice and assistance already given. These notes are submitted for publication because, whatever their scientific value, they appear to present features of practical importance and will also serve as an introduction to the new programme of research.

APPENDIX.—*Unsoundness in a Thin Plate Cast with an Atmospheric Head. An Explanation.*

In the *Transactions of the American Foundrymen's Association* for March, 1943 (vol. 50, pp. 657–710), there is an interesting paper by Brinson and Duma on the precautions necessary to cast completely sound thin plates. In the subsequent discussion an example, illustrated below, supplied by Taylor and Rominski,[4] seems to have caused much interest. As will be seen in Fig. 5, an atmospheric head was applied to the middle of the 2-in.
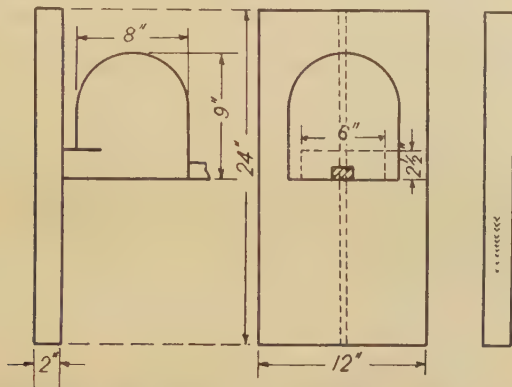

FIG. 5.—Dimensions and Position of Gates and Risers (blind riser placed half-way up the height of the casting so that part of plate was fed with benefit of gravity plus atmospheric pressure, and the other half with gravity opposing the desired direction of metal fed). Location of strip sawn from plate indicated by broken line. (Taylor and Rominski [4].)

plate and, in a result that was confirmed, the plate was unsound in the bottom half, which seems to have caused surprise. It was explained, on the one hand, as being due to faulty temperature gradients and, on the other, to turbulence during running. Neither explanation seems at all satisfactory, and differential freezing is a more probable explanation. After the columnar walls were formed in the top half, freezing proceeded more or less uniformly throughout the liquid, as the temperature did not vary greatly owing to the action of convection currents (*see* Fig. 14). The plate below the head froze from the sides and from the bottom upwards in the normal way, and in the final stages low-melting-point segregate collected at a point as high up in the casting as it could reach, just as it does in the normal top head. In this case it could not reach the head, because the material opposite the neck had already frozen at a higher temperature, owing to its higher freezing point, and other portions had been trapped by wall growth meeting across the casting.

The same explanation accounts for the result in Plates 46 and 48 of Brinson and Duma's paper, where plates 2 in. thick were sound when fed with an atmospheric head from the bottom.   Compared with the conditions existing in the specimen with top heads, convection currents induced a more uniform temperature in the liquid, and that in contact with the walls was relatively warmer.   The growth of the columnar wall was therefore slower, and there was room for a more uniform freezing of the remaining liquid without marked segregation of the secondary material.   The latter rose, being ligher in weight, was trapped by the growing primary crystals as soon as it had formed, and was therefore finely distributed throughout the middle of the casting.   Under such conditions it is not unreasonable to suppose that the solid contraction of the envelope was sufficient to balance the final contraction of solidification of the secondary liquid and produce a sound casting.   Dishing, such as occurred in Plate 46, is always a danger of these conditions, as the columnar walls are much reduced in thickness.

Following a study of the above experiment of Taylor and Rominski the present author made two further pairs of castings. The first pair, of standard size (Figs. 15 and 16), were cast vertically with the neck higher up the casting ; at the same time one neck was made of 50% greater cross-sectional area than the other but of the same length.   In other respects they were the same as example *D* in Fig. 1.   The castings were made in carbon steel with separate heads, but cast consecutively in the same heat.

The sulphur prints suggest that the example with the restricted neck (Fig. 15) had frozen inwards from the vertical walls and in doing so had trapped the secondary material, causing the dark marking on the sulphur print.   In the other (Fig. 16), growth from the walls had been restricted and the centre had frozen, in the final stages, from the top downwards with little marked segregation.   The bottom half is quite sound in both instances, though the patch of segregation opposite the runner in the first case probably indicates the position at which a cavity would have occurred if the neck had been restricted further.   The depth below the neck was too small in relation to the cross-section of the casting for unsoundness such as Taylor and Rominski found to occur in the 2 in. $\times$ 24 in. $\times$ 24-in. plate.

For the second pair of castings (Figs. 17 and 18), nickel-chromium steel was used in order to obtain a satisfactory macro-print from the section, and the castings were made on either side of a common head. The temperature of the steel in the furnace was 1625° C. (taken by an immersion couple), and the castings were poured from a 5-ton ladle at about the period when the steel from the nozzle was at its hottest.   The temperature was almost certainly considerably higher than in the previous examples.

The general form of the system of freezing is similar to that in the previous experiment, but there are remarkable differences in

PLATE I.

FIG. 6.—Sulphur Print of Example A, drained after 10 min. (cast vertically; bottom runner; top head). Cavities outlined in ink.

(a B2, drained after 8½ min.

(b B1, drained after 4½ min.

FIG. 7.—Example B (cast horizontally; whirl-gate head at one end).
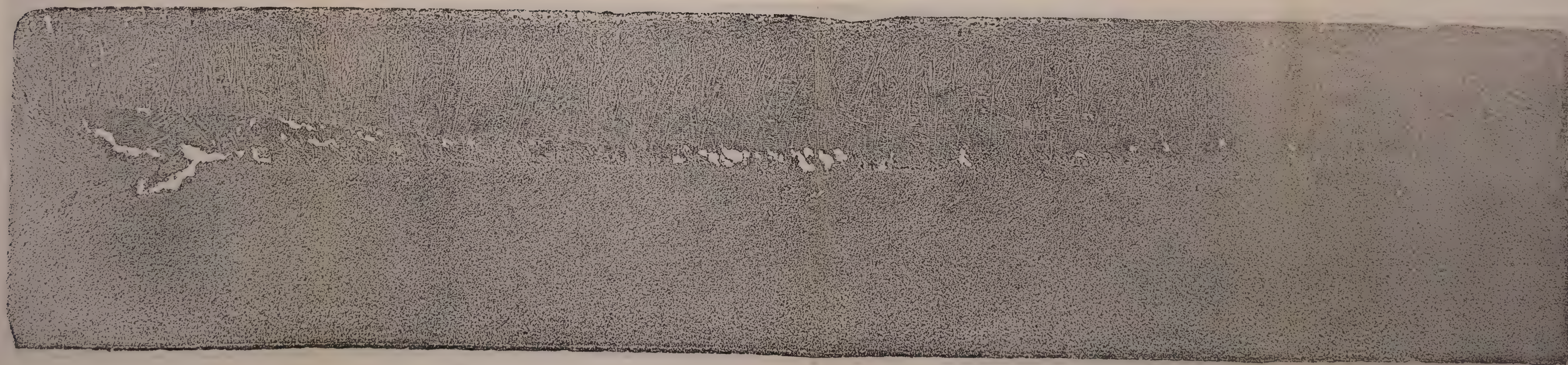
FIG. 8.—Macroprint of Example B (cast horizontally; whirl-gate head at one end).

PLATE II.

FIG. 11.—Macroprint of Sample D (cast vertically; whirl-gate head near bottom. Effect of a damp mould in causing a shrinkage cavity.
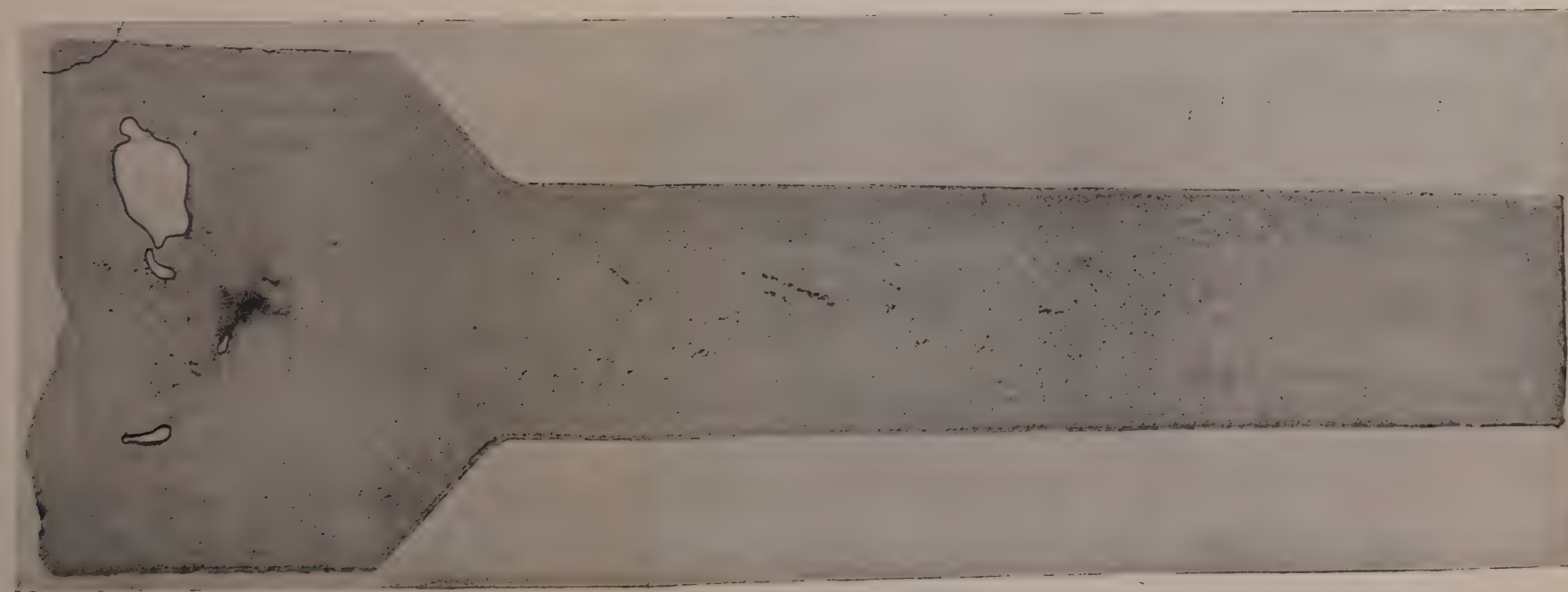
FIG. 9.—Sulphur Print of Example A (cast vertically; bottom runner; top head).
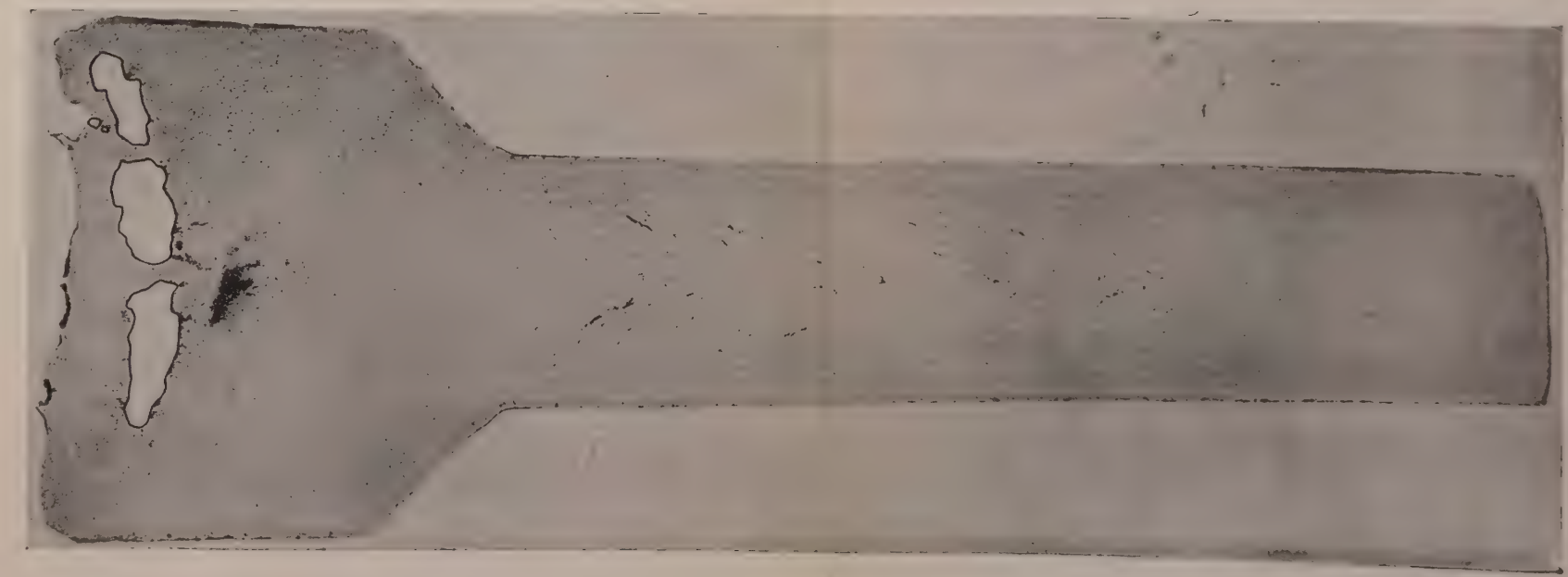
FIG. 10.—Sulphur Print of Example C (cast vertically; top head).

[Gray.

PLATE III.
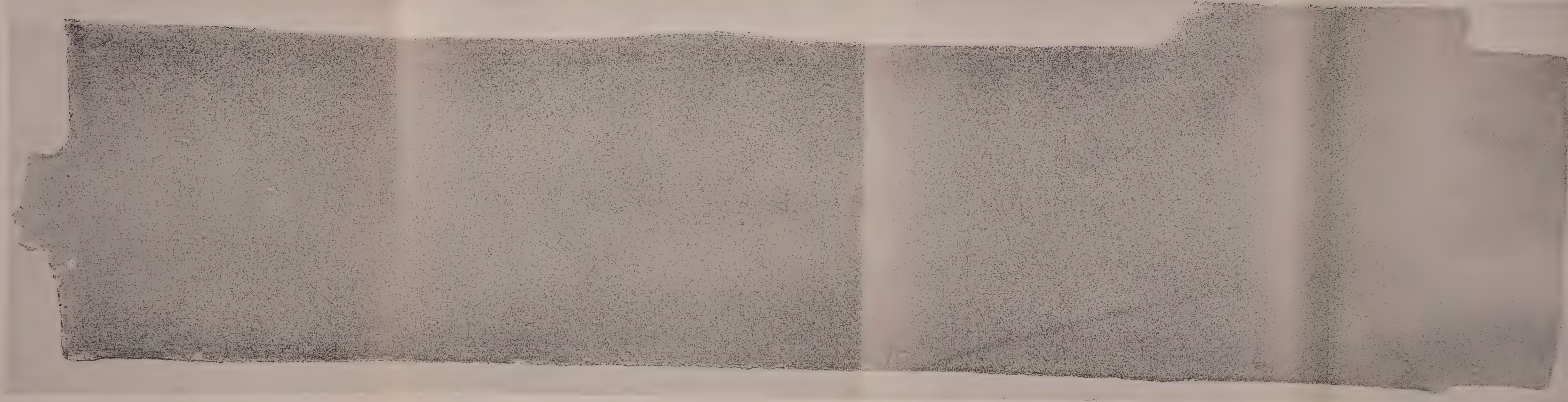
FIG. 14.—Macroprint of Example D (cast vertically; whirl-gate head near bottom).
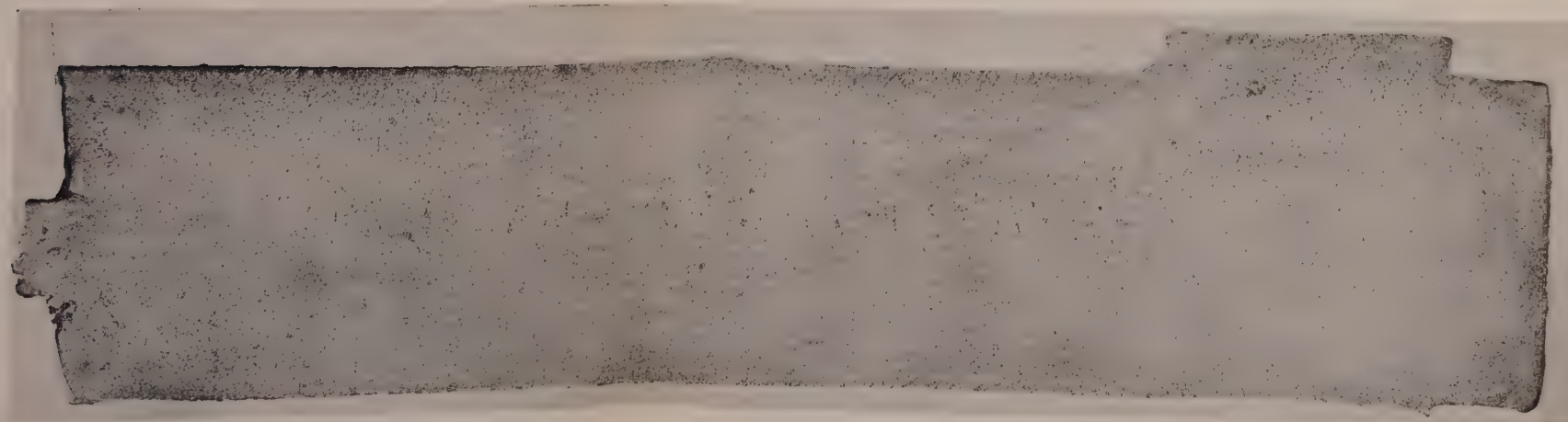
FIG. 12.—Sulphur Print of Example D (cast vertically; whirl-gate head near bottom).
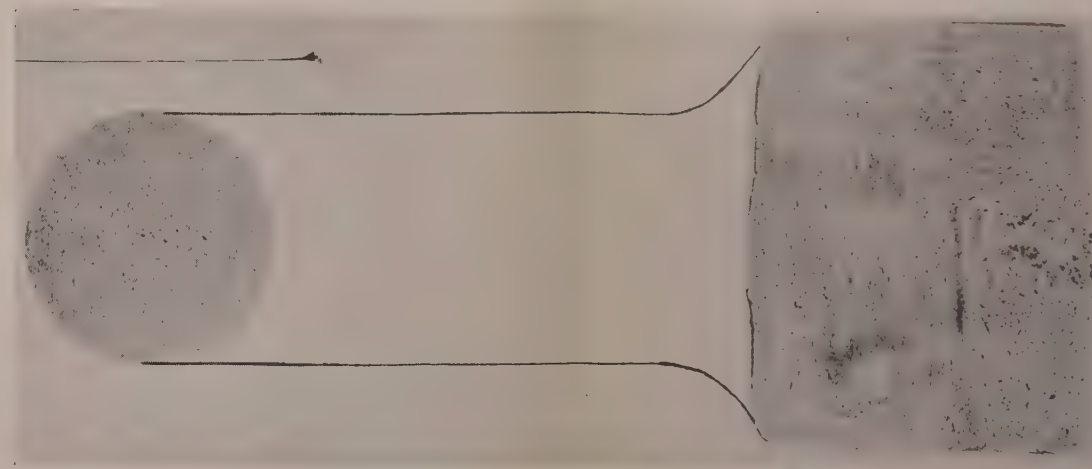
FIG. 13.—Sulphur Print of a Sectioned Casting fed through a Small Runner.

[Gray.

PLATE IV.
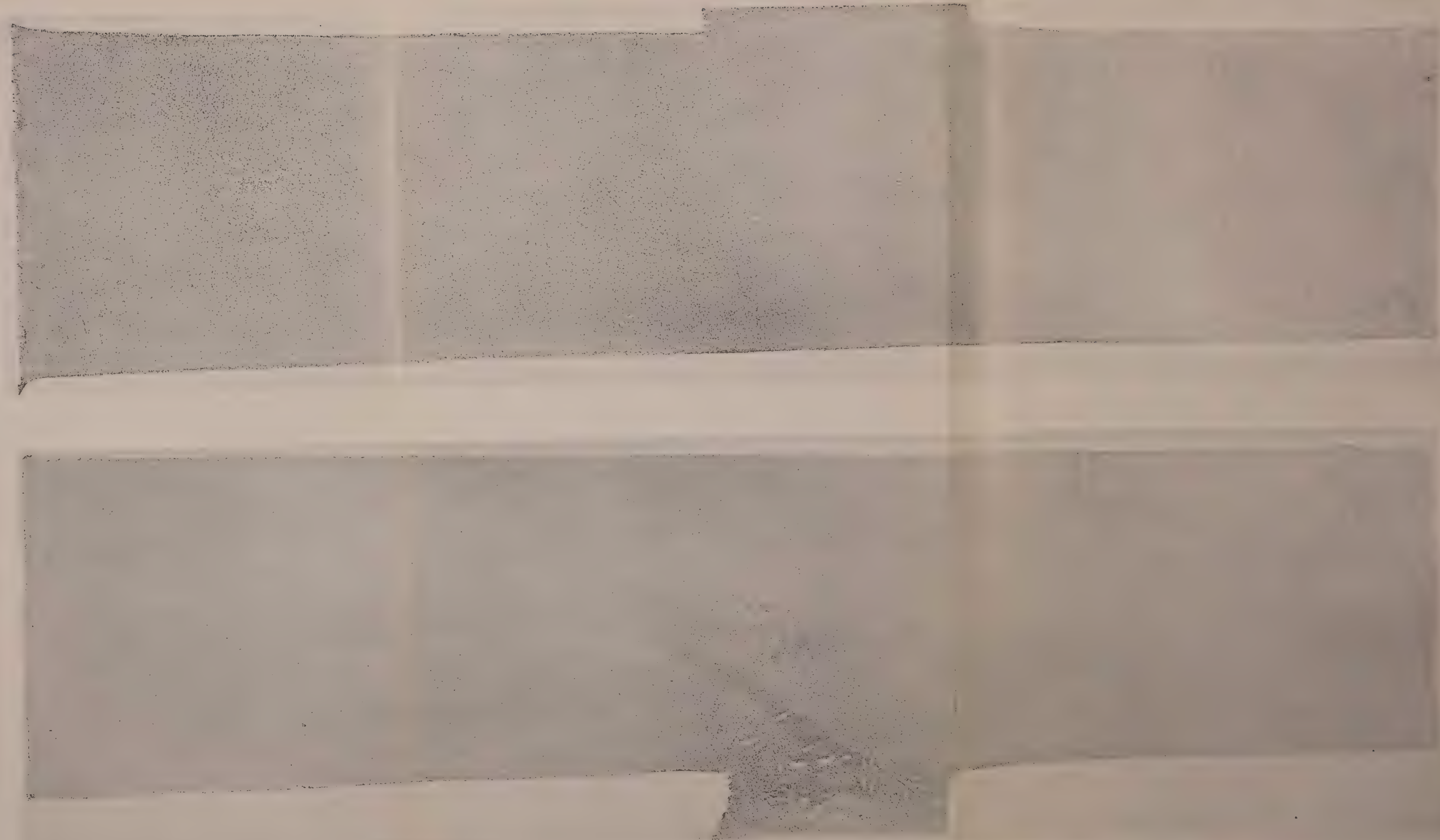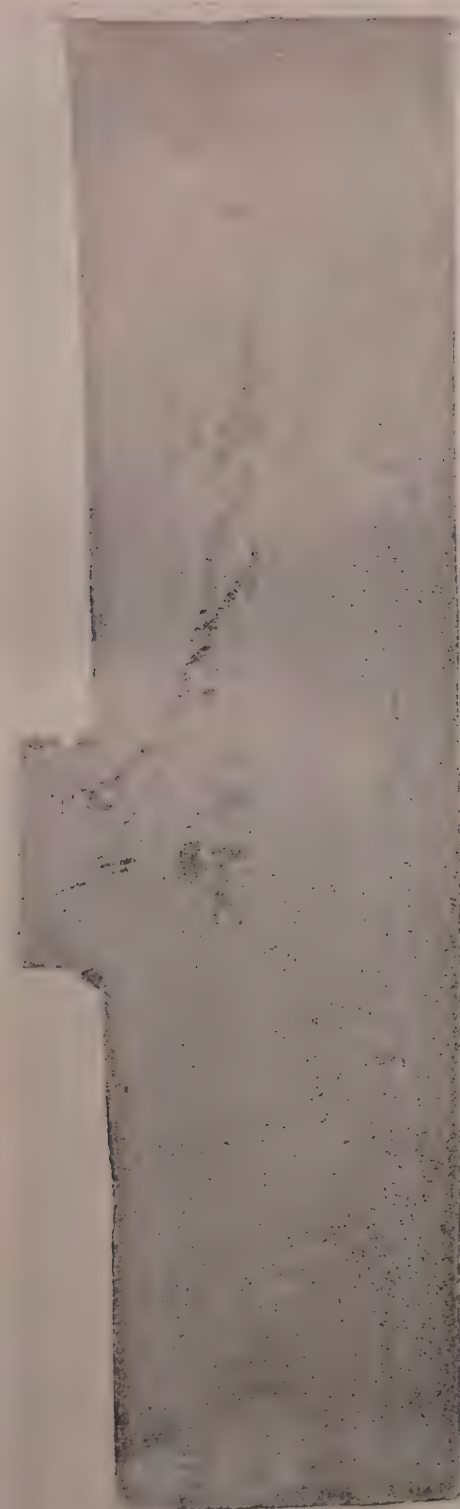
FIG. 15.—Restricted Neck.

FIG. 16.—Larger Neck.

FIGS. 15 and 16.—Sulphur Prints of Carbon-Steel Castings made Vertically; side head half way up casting. Cast consecutively in same heat.

FIG. 17. Restricted Neck.

FIG. 18.—Larger Neck.

FIGS. 17 and 18.—Macro-Prints of Nickel-Chromium Steel Castings. Cast in the same way as Figs. 15 and 16 but on the same heat.

[Gray.
[To face p. 17 v.

the crystal structure. The wall growth has taken the form of columnar dendrites in both Figs. 17 and 18, persisting to the centre in Fig. 17 but giving way to a band of equi-axed crystals in Fig. 18 when the remaining liquid had reached a fairly uniform temperature and started freezing from the top downwards.

These experiments go some way towards confirming the existence of convection currents in steel, because the dendrites on the side walls were inclined slightly towards the top of the casting, a feature which is generally accepted as indicating that there has been a temperature gradient upwards in that direction. Such a condition can have occurred only if hot steel had been transferred from lower down the casting to the top by the action of convection currents.

The heat imparted from the neck is less when it is smaller, and in consequence convection currents are less persistent. The temperature gradient across the casting is greater and the temperature in the steel near the walls is lower, causing more rapid wall growth.

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(1) G. BATTY : *Transactions of the American Foundrymen's Association*, 1934, vol. 42, p. 237.
(2) J. A. DUMA and S. W. BRINSON : *Transactions of the American Foundrymen's Association*, 1940, vol. 48, p. 225.
(3) H. F. TAYLOR and E. A. ROMINSKI : *Transactions of the American Foundrymen's Association*, 1942, vol. 50, p. 215 : *Foundry Trade Journal*, 1942, vol. 68, Oct. 15, p. 135; Oct. 22, p. 171; Oct. 29, p. 193.
(4) H. F. TAYLOR and E. A. ROMINSKI : *Transactions of the American Foundrymen's Association*, 1943, vol. 50, p. 711.

THE EFFECT OF GRAIN SHAPE ON THE MOULDING PROPERTIES OF SYNTHETIC MOULDING SANDS.[1]

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(University of Sheffield).

(Figs. 22 to 50 = Plates V. to IX.)

Paper No. 8/1944 *of the Steel Castings Research Committee* (*submitted by the Moulding Materials Sub-Committee*).

SUMMARY.

The influence of grain shape on the behaviour of sands in synthetic moulding sand mixtures bonded with clays, core oils and core compounds has been investigated, using the recently developed method of Robertson and Émodi for the assessment of grain shape. The grain angularity is shown to vary with the source from which the sand was derived originally, the conditions under which the sand deposit accumulated and the degree of consolidation of the deposit.

Typical examples of the effect of grain shape on the properties of synthetic moulding and core sand mixtures are given, and it is shown that for sands having comparable mechanical gradings the strength of mixtures prepared with angular sands is lower than that of mixtures based on rounded sands, and that the surface friability of the dried mould or core increases with the angularity of the sand. These differences are attributed to the poorer packing properties of the angular sands and to differences in the grain relationships in angular and rounded sands.

The distribution of bulk density in moulds and cores is analysed, and the relationship of the bulk-density gradient to the moulding properties is discussed and illustrated.

Some methods of minimising the disadvantageous effect of angularity of grain are suggested.

I.—INTRODUCTION.

THE study of grain shape in relation to moulding properties has been hindered by the lack of suitable methods for the comparison of grain shape. The majority of the methods are too tedious for routine work,[2] but recently R. H. S. Robertson and B. Émodi[3] have suggested a useful rapid method for comparing the shapes of sand grains. The method is based on the determination of the specific

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[1] Received January 19, 1944. This paper is published by authority of the Steel Castings Research Committee. The views expressed in it are the authors', and are not necessarily endorsed by the Committee as a body.

[2] *See*, for instance : H. Wadell, *Journal of Geology*, 1932, vol. 40, p. 443; 1933, vol. 41, p. 310; 1935, vol. 43, p. 250. E. P. Cox, *Journal of Palaeontology*, 1927, vol. 1, p. 179. A. Pentland, *Proceedings of the Royal Society of Canada*, 1927, Series 3, vol. 21, Appendix *C*, p. xciii.

[3] R. H. S. Robertson and B. Émodi, *Nature*, 1943, vol. 152, Nov. 6, p. 539.

surface (that is, the surface area of unit weight of the grains). The actual specific surface of the sand grains can be determined by an air permeability method based on the work of P. C. Carman [1] and F. M. Lea and R. W. Nurse.[2] The specific surface of a similarly graded set of spherical grains can be calculated; this value may be referred to as the theoretical specific surface. Since a sphere has the least surface area per unit volume, it follows that the ratio of the actual to the theoretical specific surface cannot be less than unity and will become progressively greater than unity as the grain shape departs further from the spherical. The ratio of actual to theoretical specific surface is defined by Robertson and Émodi as the "*coefficient of rugosity*." For a cube it has the value of 1·25 approximately, while for a regular tetrahedron the value is 1·49 approximately. The authors prefer to use the term "*coefficient of angularity*" rather than coefficient of rugosity, as the effect of surface roughness was found to be small.

II.—The Determination of the Specific Surface.

The actual specific surface is determined by passing air through the sand arranged as a cylindrical bed with its axis in the line of flow. The specific surface S_w (sq. cm. per g.) is given by the following expression:

$$S_w = \frac{1}{\delta(1-\epsilon)}\sqrt{\frac{\epsilon^3 \cdot A \cdot p_1}{K \cdot \eta \cdot Q \cdot L}} = \frac{14}{\delta(1-\epsilon)}\sqrt{\frac{\epsilon^3 \cdot A \cdot p_1}{C \cdot p_2 \cdot L}},$$

where:

δ = density of sand = 2·65 g. per c.c.
ϵ = fractional porosity of the bed = volume of pore-space/volume of bed.
A = cross-sectional area of the bed (sq. cm.).
L = length of the bed (cm.).
p_1 = pressure difference between the ends of the bed (dynes per sq. cm.).
K = a constant = 5·0 (independent of both the particle shape and the apparatus).
η = viscosity of the air.
Q = rate of air flow through the bed (c.c. per sec.).
c = flow-meter constant.
p_2 = pressure difference on flow-meter (dynes per sq. cm.).

For the mathematical development of this expression see the above-mentioned papers by Carman and by Lea and Nurse.

Carman verified the expression for a wide variety of shapes ranging from spheres to short, crimped lengths of wire. The apparatus is shown in Fig 1. The air is passed from a reservoir (not

[1] P. C. Carman, *Transactions of the Institution of Chemical Engineers*, 1937, vol. 15, p. 150; *Journal of the Society of Chemical Industry*, 1938, vol. 57, p. 225; 1939, vol. 58, p. 1.
[2] F. M. Lea and R. W. Nurse, *Journal of the Society of Chemical Industry*, 1939, vol. 58, p. 277.

shown) through concentrated sulphuric acid by means of sintered glass bubblers, and it is then passed through the sand bed contained in an inverted glass burette. The pressure difference across the bed (p_1) is recorded on a manometer. The principle underlying the flow-meter is that the rate of flow through an orifice is proportional to the pressure difference across the orifice. In the meter employed, the orifice was formed by a 2-m. length of capillary tube of 1-mm. bore.

The effect of surface roughness of the grains on the specific surface was found to be slight in a series of experiments made on an
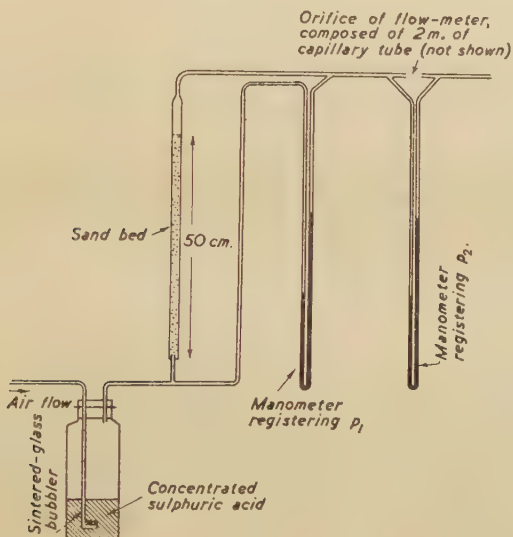
FIG. 1.—The Specific-Surface Apparatus.

inorganic salt crystallising as rectangular prisms. First of all, the specific surface of the salt was calculated from the dimensions of the prisms, measured microscopically, on the assumption that they were smooth prisms of square cross-section; over a thousand grains were measured for this purpose. Actually the grain surfaces were as rough as those of most quartz grains. Secondly, the specific surface was determined by the air permeability method. The calculated and determined values agreed to within 3%, from which it appears that the effect of surface roughness on the specific surface must be slight.

On the other hand, if the grain surfaces are dusty, the specific surface is appreciably increased. In the determination of the coefficients of angularity, the sand was washed to remove the clay and silt.

III.—Grain Shape in Relation to Grain Size.

In order to examine the relation between grain shape and grain size, sands which had accumulated under different conditions were divided into fractions according to grain size by sieving, and the coefficients of angularity of these fractions were determined. It was found that the coefficient of angularity varied with the grain size and that the general nature of this variation depended on whether the sand was obtained from an unconsolidated deposit like the Lower Greensand of Leighton Buzzard or from the crushing of a consolidated deposit such as a Carboniferous Sandstone.

(a) *Unconsolidated Sands.*

The mechanical gradings and coefficients of angularity for some unconsolidated sands are given in Table I. Curves showing the variation in the coefficients with grain size for these sands are shown in Fig 2.

The *A* (Fig. 31) and *B* (Fig. 50) sands were transported by rivers and accumulated on the sea-floor, while the sand *C* (Fig. 32) accumulated under desert conditions. In all three sands the larger grains are more rounded than the small ones. The extent of this variation is illustrated by Figs. 22 to 26. This is because the rounding of sand grains depends on the violence of the impacts between the grains, and this, in turn, depends on the weights of the grains colliding, that is, the more violent impacts occur between the larger grains. Obviously, such rounding will depend on the number of impacts and so on the duration of transport. The water-borne sands are not so rounded as the desert sand ; the effective weight of the water-borne grains was reduced by the weight of water they displaced, consequently the impacts were less violent. These sands illustrate a principle, recognised by geologists, namely, that the grains of a desert sand are usually more rounded than those of a water-borne sand.

The sands *D* (Fig. 33) and *E* (Fig. 34) were carried by glaciers for considerable distances before they were finally dumped at the end of the glacier by the melting ice. They were subjected to frost action, which tended to split the grains and so increase their angularity. This splitting affected all the grains. The fine fractions have higher coefficients of angularity than the medium and coarse fractions, because they include slivers derived from the fracturing of larger grains. Typical coarse and fine grains of sand *D* are shown in Figs. 27 and 28.

The sands *F* (Fig. 41) and *G* (Fig. 35) are rather more rounded than the water-borne *A* (Fig. 31) and *B* (Fig. 50) sands. The *F* and *G* sands were derived from the Triassic Sandstones by glacial action ; the glaciation was effective for such a short period that, although the sands must be classed as glacial, their characteristics are those of Triassic Sandstones. As such, the rounding of their constituent grains was effected under desert conditions.

TABLE I.—*The Characteristics of Some Unconsolidated Sands.*

B.S.I. Sieve No.	A.	B.	C.	D.	E.	F.	G.
Mechanical Grading.							
On 5. % .	0·0	0·0	0·0	0·0	0·0	0·0	0·0
„ 8. % .	0·2	0·0	0·0	0·0	0·0	0·0	0·0
„ 10. % .	0·2	0·1	0·0	0·0	0·0	0·0	0·0
„ 16. % .	0·6	2·0	0·0	0·0	0·2	0·1	0·1
„ 22. % .	1·1	4·9	0·0	2·5	0·3	0·2	0·2
„ 30. % .	2·5	18·0	4·4	10·5	1·3	1·3	0·9
„ 44. % .	6·7	49·3	38·1	32·8	7·6	7·0	5·8
„ 60. % .	20·0	22·1	44·7	39·7	46·2	26·5	30·0
„ 72. % .	21·2	2·3	9·6	6·2	14·0	22·5	27·7
„ 100. % .	27·2	0·8	2·6	6·4	20·8	25·0	26·1
„ 150. % .	10·8	0·3	0·3	1·8	7·8	14·1	7·7
Thro' 150. %	9·5	0·2	0·3	0·1	1·8	3·3	1·5
Total. % .	100·0	100·0	100·0	100·0	100·0	100·0	100·0
Coefficient of Angularity.							
On 22 . .	1·05	1·04	1·02	...	...	...	...
„ 30 . .	1·06	1·05	1·02	1·17	1·19	1·04	1·04
„ 44 . .	1·06	1·05	1·02	1·18	1·19	1·04	1·05
„ 60 . .	1·09	1·04	1·02	1·18	1·20	1·06	1·06
„ 72 . .	1·10	1·08	1·03	1·19	1·21	1·06	1·08
„ 100 . .	1·12	1·11	1·04	1.20	1·22	1·09	1·09
„ 150 . .	1·18	1·21	1·11	1·25	1·28	1·15	1·15
Average. .	1·14	1·05	1·03	1·17	1·19	1·08	1·08

The angularity curve for an unconsolidated sand remains almost constant when a sand deposit is traced laterally, although the mechanical grading may vary considerably, provided that the grains have not been corroded since deposition. This has been found to
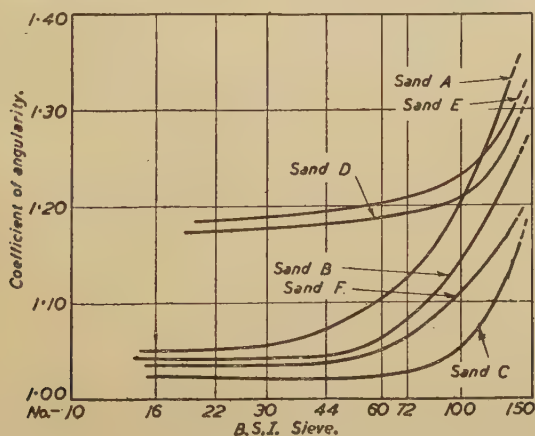

FIG. 2.—Angularity Curves for some Unconsolidated Sands.

be true of a number of deposits.   The data for some of the Permian Yellow Sands of Durham [1] are given in Table II.   These sands

TABLE II.—*The Characteristics of Some Washed Permian Yellow Sands.*

B.S.I. Sieve No.				H.	I.	J.	K.
Mechanical Grading.							
On	5.	%	.	.	0·0	0·0	0·0	0·0
,,	8.	%	.	.	1·5	2·7	0·0	1·3
,,	10.	%	.	.	0·0	0·4	0·0	0·1
,,	16.	%	.	.	0·6	1·5	0·1	0·6
,,	22.	%	.	.	0·8	3·9	0·7	3·1
,,	30.	%	.	.	4·4	12·0	1·0	6·0
,,	44.	%	.	.	15·9	14·3	2·8	23·9
,,	60.	%	.	.	28·0	18·6	5·8	29·3
,,	72.	%	.	.	17·1	10·0	18·4	13·8
,,	100.	%	.	.	19·9	13·1	39·8	13·4
,,	150.	%	.	.	11·8	23·5	31·4	8·5
Total.		%	.	.	100·0	100·0	100·0	100·0
Coefficient of Angularity.							
On	22	.	.	.	1·04	1·04	1·05	1·04
,,	30	.	.	.	1·06	1·04	1·06	1·05
,,	44	.	.	.	1·06	1·06	1·06	1·06
,,	60	.	.	.	1·08	1·08	1·08	1·07
,,	72	.	.	.	1·09	1·09	1·10	1·09
,,	100	.	.	.	1·15	1·14	1·15	1·13
,,	150	.	.	.	1·17	1·18	1·17	1·19
Average.			.	.	1·10	1·11	1·14	1·08

contain a proportion of clay grade and are stained with limonite. The sands were washed to remove the clay and cleaned with acid. The grading of the sand grade, *i.e.*, grains not passing through B.S.I. sieve No. 150, is given for the washed cleaned grains.   Though the gradings differ considerably, the coefficients of angularity of the sieve fractions agree very closely.   The weighted averages of the coefficients differ, however, owing to the differences in grading. (The weighted averages of the coefficients of angularity, such as those given in Tables I. and II., are employed in the discussion of moulding properties and will be referred to as the average coefficients.)

Typical coarse and fine grains of sand *K* are shown in Figs. 47 and 48.

(b) *Consolidated Sands.*

After the sand grains have been deposited, they may remain as an unconsolidated sediment or they may be consolidated into a

[1] For details of the localities *see* W. Davies and W. J. Rees, *Journal of The Iron and Steel Institute*, 1943, No. II., 11 P (*see* Part 5, p. 104 P).

sandstone.   Consolidation alters the shape of the quartz grains in two ways.   Solution of the quartz occurs at the points of contact between the grains so that eventually the grains have interlocking junctions.   This process may be accompanied by the deposition of the dissolved silica on the quartz grains where they adjoin the pore-spaces.   The grains tend to become more angular as they fit more closely together.

A sand composed wholly of quartz grains ultimately becomes a quartzitic sandstone.   In sands containing a proportion of clay, groups of quartz grains may form interlocking aggregates as a result of corrosion and of the addition of silica ; such aggregates are known as quartzitic aggregates.   Furthermore, the clay grade frequently contains unstable primary minerals, such as felspar, which decompose, thus liberating alkaline solutions that corrode the quartz grains and so assist in the alteration of grain shape.

When quartzitic sandstones or sandstones containing quartzitic aggregates are crushed to produce sand, the resulting sand grains are derived in two ways : Grains which are only slightly interlocked separate as single grains, whereas those which are well interlocked to form quartzitic aggregates do not separate as single grains but the whole aggregate fractures conchoidally without reference to the original grain junctions.   Such aggregates usually yield angular composite grains together with fine slivers of quartz.   The composite character of some grains of sand M is illustrated in Fig. 29.

This fracturing of the quartzitic aggregates can be demonstrated by reference to the quartzitic sandstones of the Cefn-y-Fedw series of North Wales.   These sandstones show every variation from open-textured rocks with practically no interlocking to compact rocks in which the pore-space has been almost eliminated.   Microscopic examination shows that the constituent grains are of uniform size. On crushing the open-textured variety, a well-graded sand is obtained.   As the texture becomes more compact, the resulting sand becomes less well-graded until ultimately it becomes double-graded, that is, it is composed of grains coarser and finer than the constituent grains of the uncrushed rock.   Micro-examination shows that the coarse grains are composite.   The grains derived from the open-textured rock are polygonal, whilst those from the compact rocks tend to be tetrahedral.

Sandstones like those from which sands such as M and L are produced are composed of quartzitic aggregates and clay ;   in addition there are quartz grains which are not interlocked.   A typical section of one of these rocks is shown in Fig. 30.   These sandstones are crushed and the resulting sand is washed and graded. The characteristics of some of these sands are given in Table III., and their angularity curves are shown in Fig. 3.   These curves are U-shaped.   The coarse and fine grains are derived from the quartzitic aggregates and are more angular than the medium grains, the latter being single grains which were not interlocked.   As is to be expected,

TABLE III.—*The Characteristics of Sands Derived from Crushed Sandstones.*

B.S.I. Sieve No.	L.				M.			
	L1.	L2.	L3.	L4.	M1.	M2.	M3.	M4.
Mechanical Grading.								
On 5. %	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0
,, 8. %	0·1	0·1	0·0	0·1	0·0	0·0	0·0	0·0
,, 10. %	0·1	0·1	0·0	0·1	0·0	0·0	0·0	0·0
,, 16. %	1·1	0·8	0·2	0·4	0·0	0·6	1·7	0·1
,, 22. %	5·4	4·2	0·3	0·5	0·1	4·9	8·1	0·2
,, 30. %	11·0	11·3	0·9	0·9	0·4	10·6	19·0	5·4
,, 44. %	21·8	22·8	3·7	2·4	8·5	18·7	21·4	39·5
,, 60. %	31·3	34·4	15·3	5·9	19·3	23·0	18·0	33·3
,, 72. %	12·3	12·8	14·2	7·0	21·0	15·4	11·1	11·8
,, 100. %	11·0	8·5	25·7	22·5	34·5	18·9	14·4	7·5
,, 150. %	4·4	3·6	24·8	34·0	15·0	6·7	5·5	1·8
Thro' 150. %	1·5	1·4	14·9	26·2	1·2	1·2	0·9	0·4
Total. %	100·0	100·0	100·0	100·0	100·0	100·0	100·0	100·0
Coefficient of Angularity.								
On 30	1·28	1·31	...	...	...	1·39	1·39	1·39
,, 44	1·25	1·25	...	...	...	1·26	1·23	1·24
,, 60	1·18	1·19	1·20	1·20	1·19	1·19	1·17	1·18
,, 72	1·16	1·15	1·17	1·18	1·14	1·13	1·13	1·14
,, 100	1·24	1·22	1·23	1·25	1·16	1·14	1·14	1·15
,, 150	1·40	1·39	1·33	1·36	1·25	1·30	1·28	1·27
Average.	1·23	1·24	1·27	1·29	1·18	1·22	1·21	1·20

grains of the same size from the same source have almost identical coefficients of angularity. The average coefficients differ because of the difference in the gradings. Thus a sand composed almost wholly of grains passing 60-mesh and retained by 72-mesh would
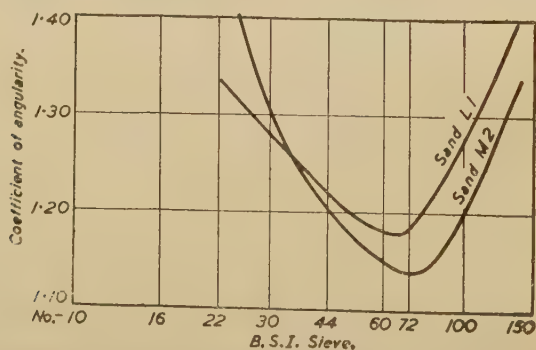

FIG. 3.—Angularity Curves for Sands Produced by Washing Two Crushed Sandstones.

have a lower average coefficient than one composed of grains passing 30-mesh and retained by 44-mesh. Typical grains of sands $L1$ to $L4$ and $M1$, $M3$ and $M4$ are shown in Figs. 44, 36 to 40 and 45.

IV.—Moulding Properties of Angular and Rounded Sand Grains.

The moulding properties of a sand mix depend on the nature and proportion of the bond and on the characteristics of the sand grade. The latter may be grouped under three heads, *viz.*, mechanical grading, grain shape and the nature of the grain surfaces. A series of comparative tests were made in each of which the bond was constant and the mechanical grading and the nature of the grain
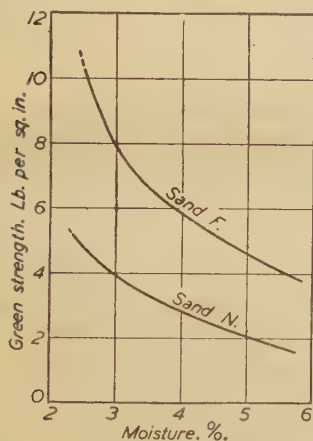

FIG. 4.—Green Strength of Sands F and N Bonded with 5% Fulbond No. 1. A.F.A. test-pieces rammed 10 times.
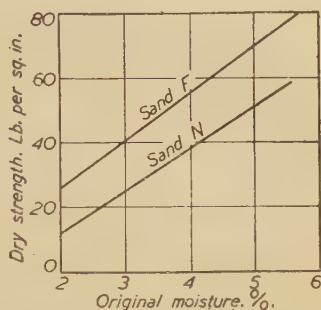
FIG. 5.—Dry Strength of Sands F and N Bonded with 5% Fulbond No. 1. A.F.A. test-pieces rammed 10 times.

surfaces were as nearly similar as possible. The mechanical gradings were compared by means of B.S.I. sieves shaken on a Rotap sieving machine for 15 min., and the grain surfaces were compared under the microscope. In this way it was possible to isolate the effect of grain shape on the moulding properties.

The sand mixes were bonded in several ways, some with clay and water and others with core oil or core compound. Mixtures containing both clay and organic bond were also used.

(a) *Sand Mixes with a Clay Bond.*

The effect of grain shape on the moulding properties of clay-bonded sands is illustrated by mixes of N and F sands bonded with 5% of Fulbond No. 1. The green-strength/moisture and dry-strength/original-moisture curves are shown in Figs. 4 and 5; the

TABLE IV.—*The Moulding Properties of* N *and* F *Sand Mixes.*

Sands bonded with 5% Fulbond No. 1.   A.F.A. test-pieces rammed 10 times.

Sand N.						
Moisture content. %	.	.	.	2·5	3·0	4·0	5·0
Bulk density. G. per c.c.	.	.	1·66	1·67	1·70	1·71
Permeability number	.	.	. 131	127	110	100
Green strength. Lb. per sq. in.	.	. 4·8	3·9	2·8	2·0
Dry strength. Lb. per sq. in.	.	18	25	38	51
Sand F.						
Moisture content. %	.	.	.	2·5	3·0	4·0	5·0
Bulk density. G. per c.c.	.	.	1·67	1·68	1·72	1·73
Permeability number	.	.	. 127	124	100	95
Green strength. Lb. per sq. in.	.	. 10·5	7·8	5·8	4·6
Dry strength. Lb. per sq. in.	.	34	41	56	70

data for these curves are given in Table IV.   It will be seen that, for a given moisture content, both the green and dry strengths of the F sand mix are much higher than those of the N sand mix.   The cumulative-grading and angularity curves for the two sands are shown in Fig. 6 ; the corresponding data are given in Table V. Typical grains of these sands are shown in Figs. 41 and 42.   The two sands are equally well-graded.   This comparison implies that the inferior moulding properties of the N mix are due to the fact that the N sand grains are more angular than the F sand grains.

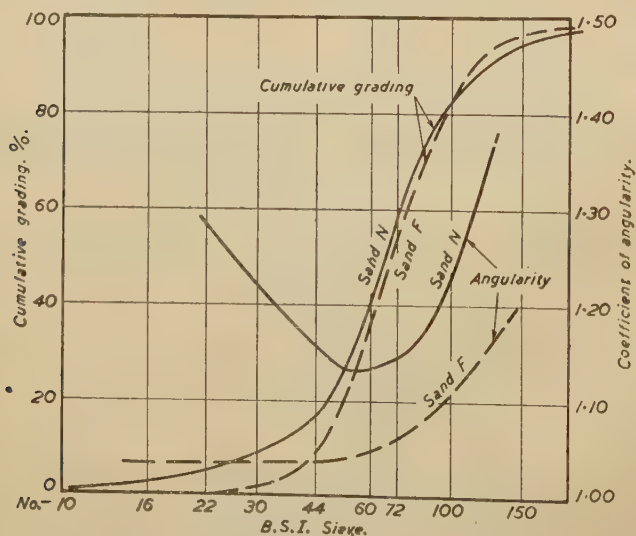FIG. 6.—Characteristics of Sands F and N.

TABLE V.—*Characteristics of Sands* N *and* F.

B.S.I. Sieve No.	Mechanical Grading.		Coefficient of Angularity.	
	N.	*F.*	*N.*	*F.*
On 5. %	0·0	0·0	...	...
,, 8. %	0·0	0·0	...	...
,, 10. %	0·1	0·0	...	...
,, 16. %	2·8	0·1	...	...
,, 22. %	2·4	0·2	...	...
,, 30. %	4·8	1·3	1·25	1·04
,, 44. %	7·2	7·0	1·19	1·04
,, 60. %	22·4	26·5	1·13	1·06
,, 72. %	20·6	22·7	1·14	1·06
,, 100. %	22·1	25·0	1·17	1·09
,, 150. %	12·9	14·1	1·35	1·15
Thro' 150. %	4·7	3·1	...	...
Total. %	100·0	100·0	Av. 1·20	1·08

	N.	*F.*
Specific surface. Sq. cm. per g.	117·0	116·0
Chemical analyses.		
SiO_2. %	95·96	97·16
TiO_2. %	0·03	0·02
Fe_2O_3. %	0·12	0·15
Al_2O_3. %	2·42	1·46
CaO. %	0·12	0·14
MgO. %	0·24	0·18
K_2O. %	0·35	0·38
Ignition loss. %	0·70	0·45
Total. %	99·94	99·94

Less detailed comparisons were made between the sands *M*4 and *O*. The moulding properties are recorded in Table VI., while the sand characteristics are given in Table VII. and illustrated

TABLE VI.—*The Moulding Properties of Sands* M4 *and* O *Bonded with* 5% *of Wyoming Bentonite.*

	*M*4.	*O*.
Moisture content. %	2·0	2·0
A.F.A. test-pieces rammed 3 times.		
Bulk density. G. per c.c.	1·59	1·63
Green permeability number	370	380
Green strength. Lb. per sq. in.	4·1	7·1
Dry strength. Lb. per sq. in. .	15	30
A.F.A. test-pieces rammed 10 times.		
Bulk density. G. per c.c.	1·64	1·67
Green permeability number	300	350
Green strength. Lb. per sq. in.	5·8	8·3
Dry strength. Lb. per sq. in. .	25	45

by Fig. 7. Typical grains of these sands are shown in Figs. 45 and 46. These two sands are decidedly coarser than the F and N sands; the $M4$ sand grains are angular while the O sand grains are rounded. The green and dry strengths of the $M4$ mix are decidedly lower than those of the O mix. The permeability numbers for the test-pieces rammed 3 times are almost equal, but for test-pieces rammed 10

TABLE VII.—*The Characteristics of Sands* M4 *and* O.

B.S.I. Sieve No.				Mechanical Grading.		Coefficient of Angularity.	
				*M*4.	*O*.	*M*4.	*O*.
On 5. %	.	.	.	0·0	0·0	...	...
,, 8. %	.	.	.	0·0	0·2	...	...
,, 10. %	.	.	.	0·0	0·0	...	...
,, 16. %	.	.	.	0·1	0·2	...	...
,, 22. %	.	.	.	0·2	1·7	...	...
,, 30. %	.	.	.	5·4	11·8	1·39	1·05
,, 44. %	.	.	.	39·5	40·3	1·24	1·04
,, 60. %	.	.	.	33·3	36·6	1·18	1·05
,, 72. %	.	.	.	11·8	5·2	1·14	1·06
,, 100. %	.	.	.	7·5	2·6	1·15	1·11
,, 150. %	.	.	.	1·8	1·2	1·27	1·18
Thro' 150. %	.	.	.	0·4	0·2	...	...
Total. %	.	.	.	100·0	100·0	Av. 1·20	1·05

	*M*4.	*O*.
Specific surface. Sq. cm. per g. . .	72·2	56·7
Chemical analyses.		
SiO$_2$. %	98·47	98·95
TiO$_2$. %	0·04	0·02
Fe$_2$O$_3$. %	0·19	0·14
Al$_2$O$_3$. %	0·68	0·38
CaO. %	0·08	0·08
MgO. %	0·08	0·10
K$_2$O. %	0·18	0·12
Ignition loss. %	0·20	0·16
Total. %	99·92	99·95

times the $M4$ mix has a rather lower permeability. The ratio of strength of test-pieces rammed 10 times to that of test-pieces rammed 3 times is greater for the $M4$ mix than for the O mix. In other words, increased ramming causes more rearrangement of the grains in the $M4$ mix than in the O mix.

The difference in strength between mixes composed of angular and of rounded sand grains might at first sight be attributed to the greater specific surface of the angular sand. The thickness of the bond on the angular grains would be less than that on the rounded grains. If the proportion of bond in the angular sand mix is increased in proportion to the difference in specific surface the
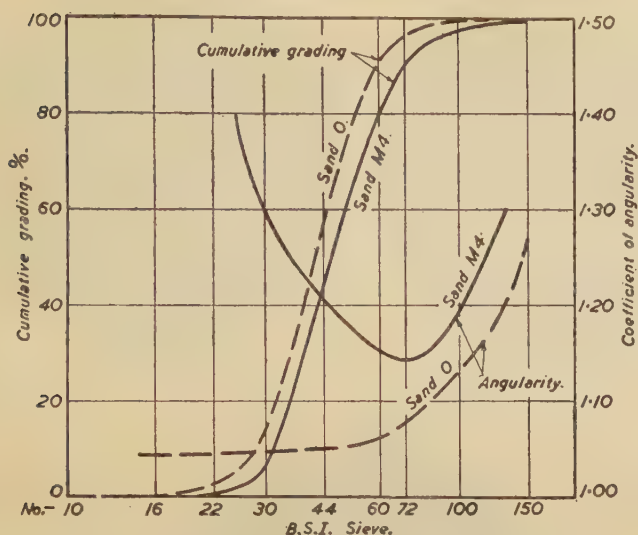
FIG. 7.—Characteristics of Sands M4 and O.

strength is increased but is still much lower than that of the corresponding rounded sand mix.

A further difference between the angular and rounded sand mixes is in the ease with which the A.F.A. test-pieces strip.   The
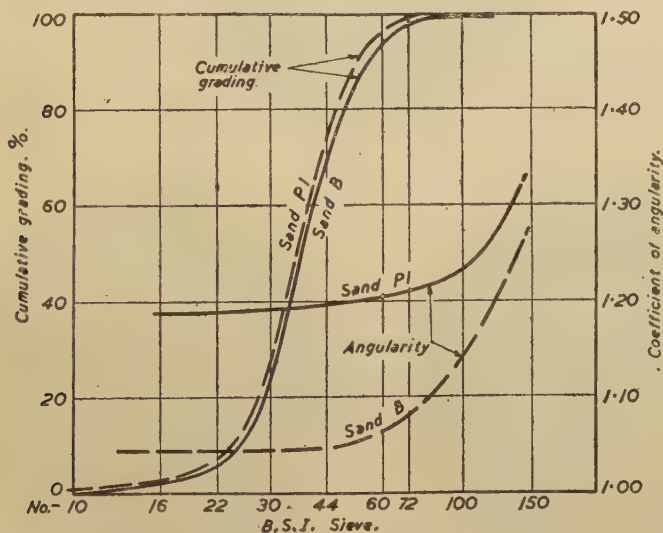

FIG. 8.—Characteristics of Sands P1 and B.

test-pieces of the angular sand mixes are always more difficult to strip, and their edges are more friable than those of the rounded sand mixes. This difference in stripping decreases as the moisture content of the mixes is increased, but is always apparent.

(b) *Sand Mixes with an Organic Bond.*

Comparative tests were made on sands B and $P1$, which are similar in grading. The characteristics of the two sands are given

TABLE VIII.—*The Characteristics of* P, P1 *and* B *Sands.*

B.S.I. Sieve No.	Mechanical Grading.			Coefficient of Angularity.		
	P.	*P1.*	*B.*	*P.*	*P1.*	*B.*
On 5. % .	0·0	0·0	0·0	...	...	...
,, 8. % .	0·1	0·4	0·0	...	...	...
,, 10. % .	0·1	0·2	0·1	...	...	...
,, 16. % .	1·0	1·6	2·0	...	...	...
,, 22. % .	1·0	3·6	4·9	1·19	1·19	1·04
,, 30. % .	3·2	19·7	18·0	1·19	1·19	1·05
,, 44. % .	14·7	46·4	49·3	1·19	1·19	1·05
,, 60. % .	49·0	22·6	22·1	1·20	1·20	1·04
,, 72. % .	15·9	4·3	2·3	1·21	1·21	1·08
,, 100. % .	13·3	0·9	0·8	1·22	1·22	1·11
,, 150. % .	1·4	0·2	0·3	1·28	1·28	1·21
Thro' 150. %	0·2	0·1	0·2	...	...	...
Total. % .	99·9	100·0	100·0	Av. 1·20	1·19	1·05

	P.	*B.*
Specific surface. Sq. cm. per g. . .	81·9 ($P1$ 69·2)	57·1
Chemical analyses.		
SiO_2. %	94·90	98·75
TiO_2. %	0·06	0·02
Fe_2O_3. %	0·95	0·16
Al_2O_3. %	2·19	0·47
CaO. %	0·12	0·12
MgO. %	0·34	0·08
K_2O. %	0·76	0·14
Ignition loss. %	0·60	0·20
Total. %	99·92	99·94

in Table VIII. and illustrated by Fig. 8. The data for sand P, from which sand $P1$ was obtained by regrading, are included in the Table for comparison. The gradings are alike, but the $P1$ sand is much more angular than the B sand. Typical grains of the two sands are shown in Figs. 49 and 50. The tensile strengths obtained with different organic bonds are recorded in Table IX. In each case the tensile strength of the $P1$ sand mix is lower than that of the corresponding B sand mix, though the difference is not so marked with some bonds as with others.

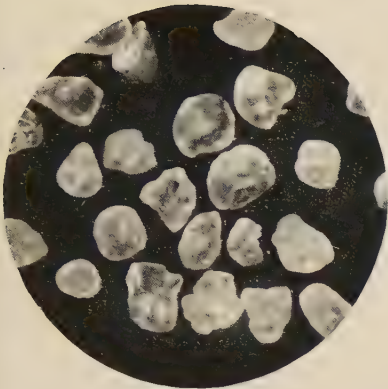The tests recorded in Table X. show the relation between the

PLATE V.

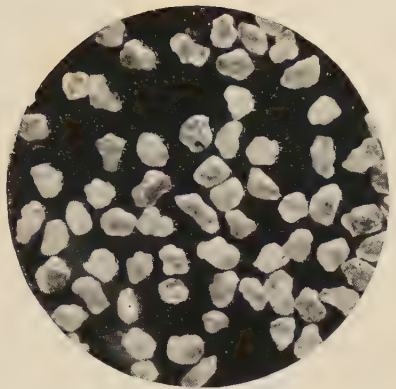Fig. 22.—B.S.I. Sieve Fraction −30/+44. Co-efficient of angularity 1·05. × 15, reflected light.

Fig. 23.—B.S.I. Sieve Fraction −60/+72. Co-efficient of angularity 1·08. × 15, reflected light.
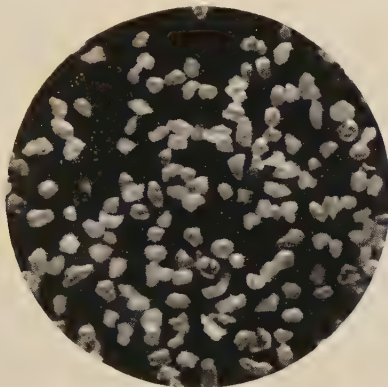
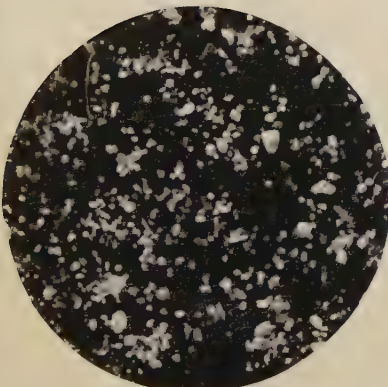Fig. 24.—B.S.I. Sieve Fraction −100/+150. Co-efficient of angularity 1·21. × 15, reflected light.

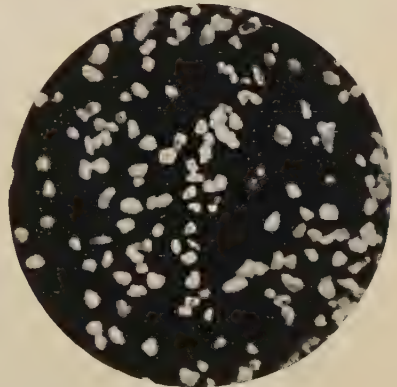Fig. 25.—B.S.I. Sieve Fraction −150. × 15, reflected light.

Fig. 26.—As Fig. 25. × 75.

FIGS. 22 to 26.—Variation of Grain Shape with Grain Size. Sand *B*.

(Micrographs reduced to four-fifths linear in reproduction.)

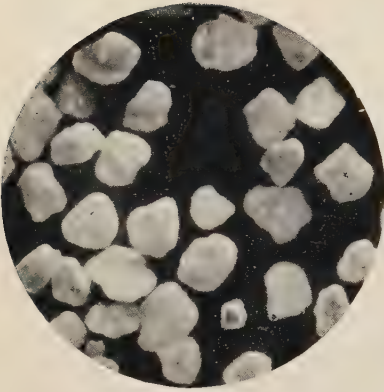PLATE VI.

FIG. 27.—B.S.I. Sieve Fraction −30/+44. Coefficient of angularity 1·18. × 15, reflected light.

FIG. 28.—B.S.I. Sieve Fraction −72/+100. Coefficient of angularity 1·20. × 15, reflected light.

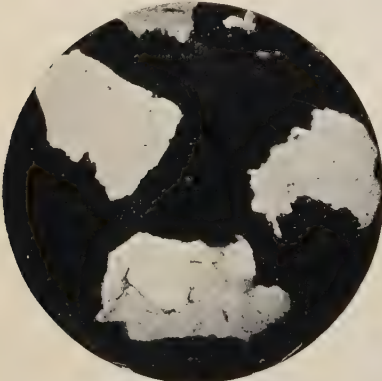FIGS. 27 and 28.—Variation of Grain Shape with Grain Size. Sand D.

FIG. 29.—Grains Derived from Fracture of Quartzitic Aggregates; one grain composite, formed by fracture independent of the original grain junctions. Sand M. × 50, crossed nicols.
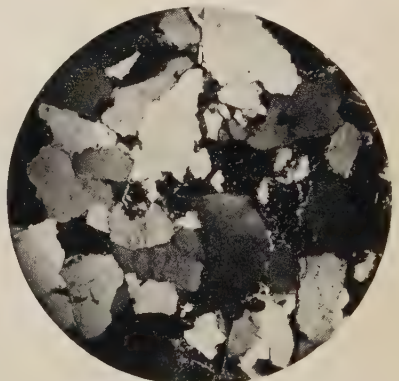
FIG. 30.—Section of L Sandstone; well-developed quartzitic aggregates with interstitial kaolinite. × 30, crossed nicols.

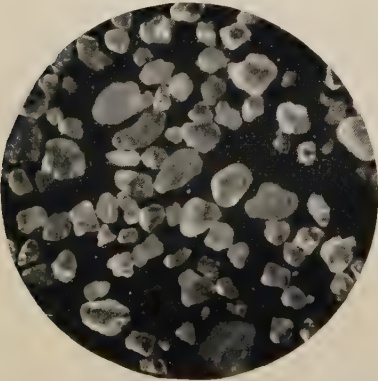FIGS. 29 and 30.—The Crushing of Sandstones.

FIG. 31.—Sand A. Average coefficient of angularity 1·14. × 15.

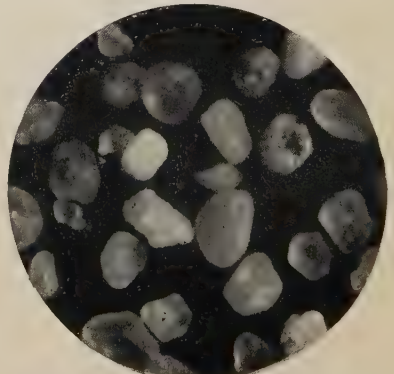FIG. 32.—Sand C. Average coefficient of angularity 1·03. × 15.

Micrographs reduced to four-fifths linear in reproduction.)

[Davies and Rees.

PLATE VII.

FIG. 33.—Sand *D*. Average coefficient of angularity 1·17. × 15.

FIG. 34.—Sand *E*. Average coefficient of angularity 1·19. × 15.

FIG. 35.—Sand *G*. Average coefficient of angularity 1·08. × 15.

FIG. 36.—Sand *L*2. Average coefficient of angularity 1·24. × 15.

FIG. 37.—Sand *L*3. Average coefficient of angularity 1·24. × 15.

FIG. 38.—Sand *L*4. Average coefficient of angularity 1·29. × 15.

(Micrographs reduced to four-fifths linear in reproduction.)

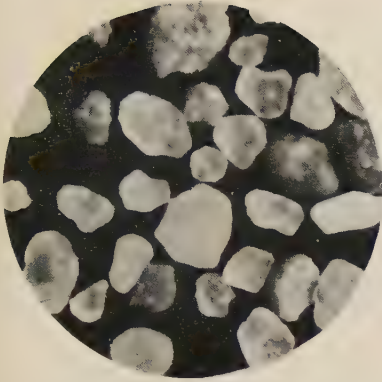[*Davies and Rees.*

PLATE VIII.
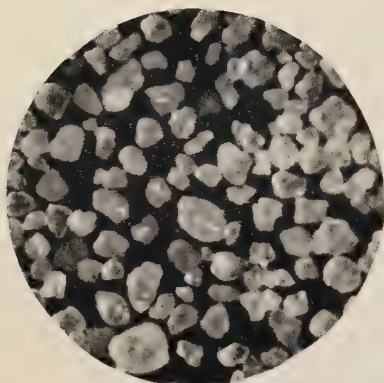
FIG. 39.—Sand $M1$. Average coefficient of angularity 1·18. × 15.
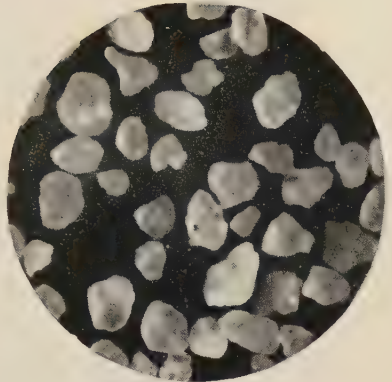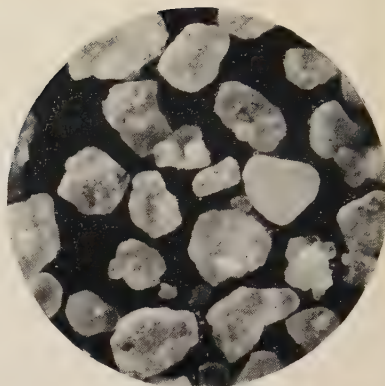
FIG. 40.—Sand $M3$. Average coefficient of angularity 1·21. × 15.
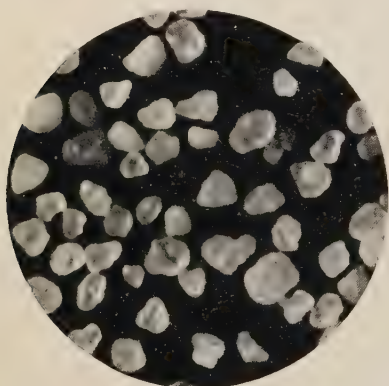
FIG. 41.—Sand F. Average coefficient of angularity 1·08. × 15.
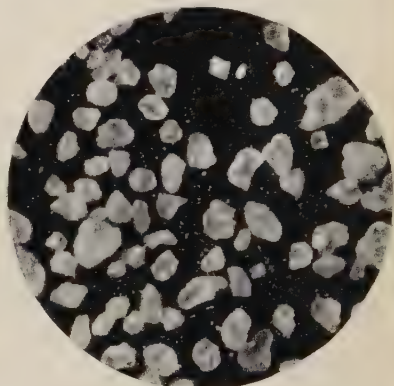
FIG. 42.—Sand N. Average coefficient of angularity 1·20. × 15.
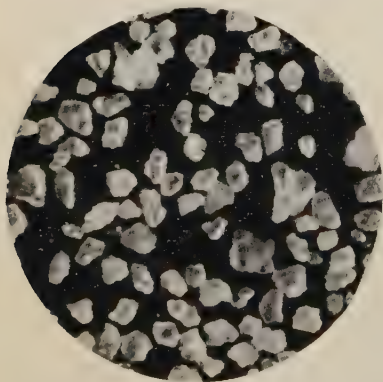
FIG. 43.—Sand R. Average coefficient of angularity 1·28. × 15.
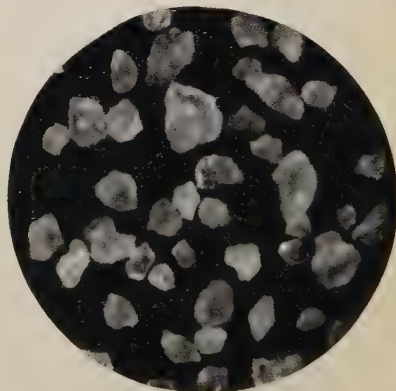
FIG. 44.—Sand $L1$. Average coefficient of angularity 1·23. × 15.

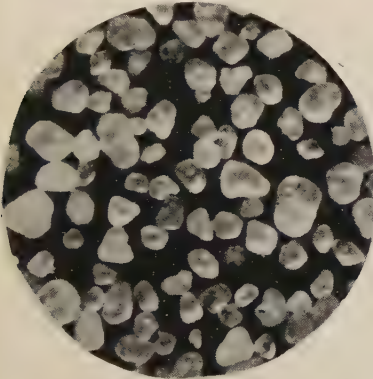(Micrographs reduced to four-fifths linear in reproduction.)

[*Davies and Rees.*

PLATE IX.
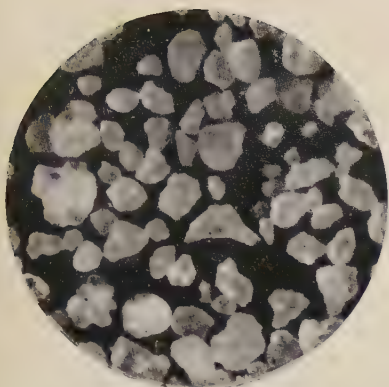
Fig. 45.—Sand M4. Average coefficient of angularity 1·20. × 15.
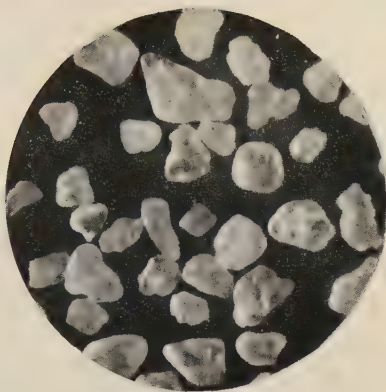
Fig. 46.—Sand O. Average coefficient of angularity 1·04. × 15.
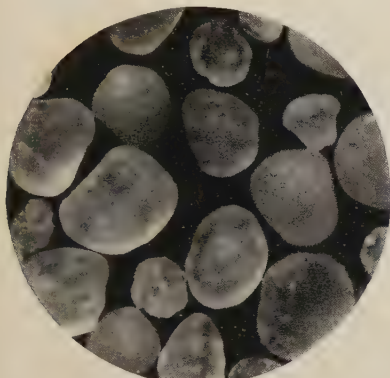
Fig. 47.—Sand K. B.S.I. sieve fraction −22/+44. Coefficient of angularity 1·05. × 15.
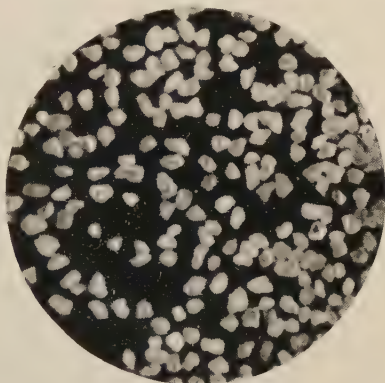
Fig. 48.—Sand K. B.S.I. sieve fraction −100/+150. Coefficient of angularity 1·19. × 15.
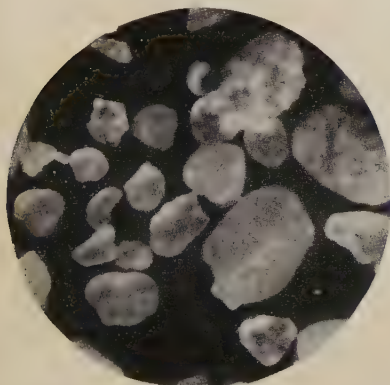
Fig. 49.—Sand P. Average coefficient of angularity 1·20. × 15.
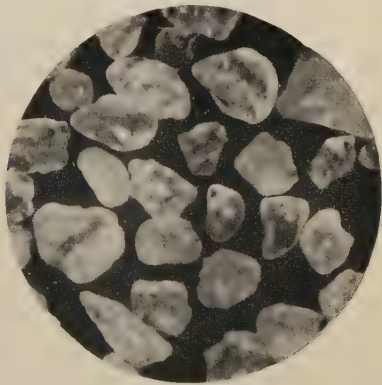
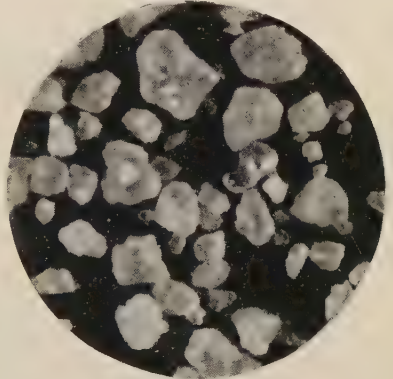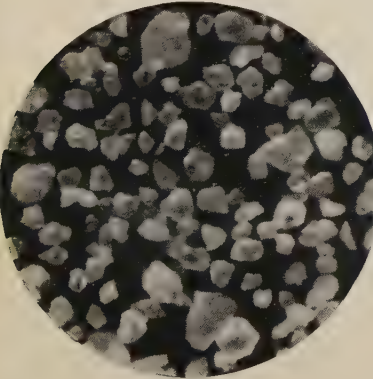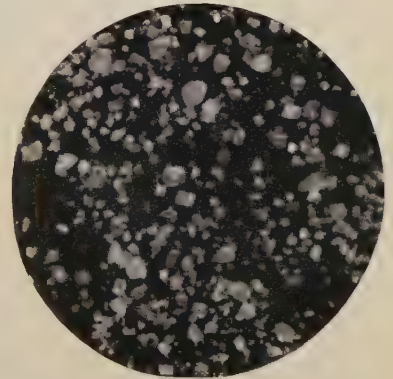Fig. 50.—Sand B. Average coefficient of angularity 1·05. × 15.

(Micrographs reduced to four-fifths linear in reproduction.)

[Davies and Rees.
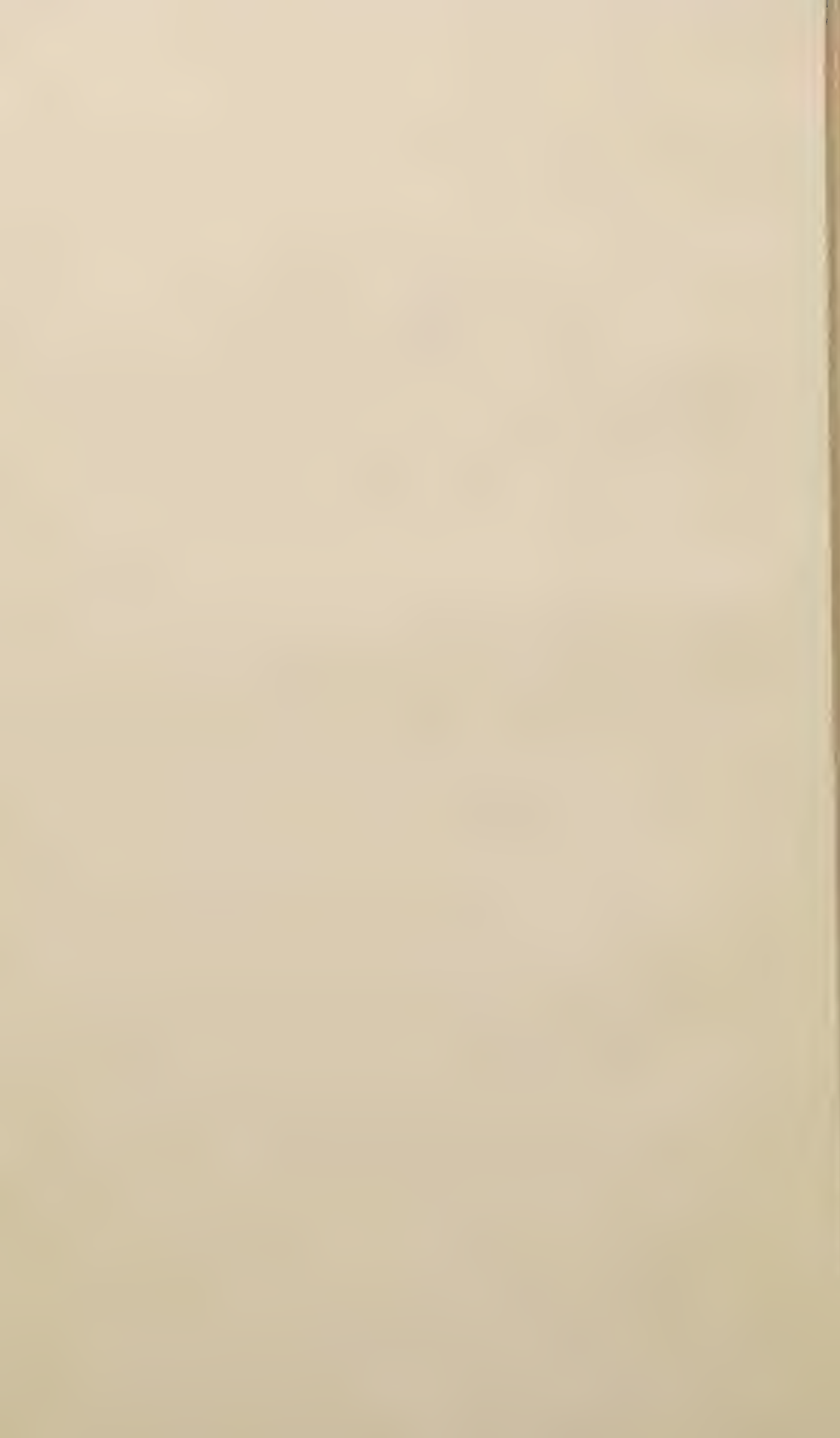
TABLE IX.—*The Tensile Strengths of* P1 *and* B *Sand Mixes with Different Bonds* (*lb. per sq. in.*).

Bond.	P1.	B.
2·5% Core oil *ex* iron foundry	90	225
4·0% Black core compound + 0·6% moisture . .	160	250
4·0% Semi-solid core compound + 0·6% moisture .	120	210
4·0% S.S.A. core compound + 0·6% moisture. .	150	230

tensile strength and the proportion of bond used with these two sands. It will be seen that the proportion of core oil in the P1 sand has to be increased to 4·0% before its tensile strength is equal to that of the B sand mix with 2·5% of core oil, that is, the proportion of

TABLE X.—*The Tensile Strengths of* P1 *and* B *Sand Mixes with Different Proportions of Core Oil* (*lb. per sq. in.*).

Bond. %.	P1.	B.	Bond. %.	P1.	B.
2·5	90	225	3·5	180	270
3·0	135	245	4·0	220	295

bond has to be increased by 60%. The specific surface of the P1 sand is 20% higher than that of the B sand ; thus the difference in tensile strength is not due simply to the difference in the thickness of the film of bond on the sand grains consequent on the difference between the two sands. Tests were also made on sands F and R.
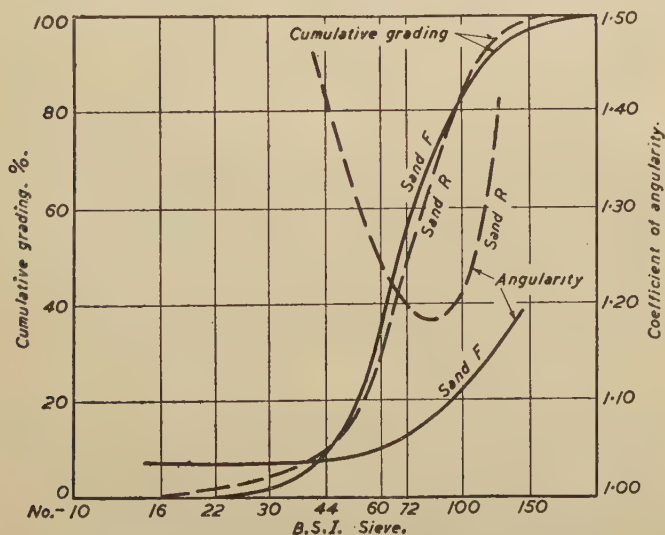
FIG. 9.—Characteristics of Sands R and F.

D

The characteristics of these two sands are given in Table XI. and Fig. 9, and typical grains are shown in Figs. 41 and 43. The gradings are similar, but sand R is much more angular than sand F.

TABLE XI.—*The Characteristics of* R *and* F *Sands.*

B.S.I. Sieve No.	Mechanical Grading.		Coefficient of Angularity.	
	$R.$	$F.$	$R.$	$F.$
On 5. %	0·0	0·0	...	...
,, 8. %	0·0	0·0	...	...
,, 10. %	0·0	0·0	...	...
,, 16. %	0·2	0·1	...	...
,, 22. %	1·2	0·2	...	...
,, 30. %	2·4	1·3	...	1·04
,, 44. %	5·0	7·0	1·53	1·04
,, 60. %	21·4	26·5	1·34	1·06
,, 72. %	15·4	22·5	1·22	1·06
,, 100. %	37·0	25·0	1·18	1·09
,, 150. %	17·4	14·1	1·40	1·15
Thro' 150. %	0·0	3·3	...	...
Total. %	100·0	100·0	Av. 1·28	1·08

	$R.$	$F.$
Specific surface. Sq. cm. per g.	142·6	110·5
Chemical Analyses.		
SiO_2. %	99·03	97·16
TiO_2. %	0·01	0·02
Fe_2O_3. %	0·03	0·15
Al_2O_3. %	0·41	1·46
CaO. %	0·04	0·14
MgO. %	0·08	0·18
K_2O. %	0·12	0·38
Ignition loss. %	0·20	0·45
Total. %	99·92	99·94

The tensile strengths with different bonds are recorded in Table XII. The R sand gives a lower strength than the F sand.

All these tests with organic bonds show that sands composed of angular grains give lower tensile strengths than those composed of

TABLE XII.—*The Tensile Strengths of* R *and* F *Sands with Different Bonds* (lb. *per sq. in.*).

Bond.	$R.$	$F.$
2·5% Core oil	190	290
2·5% Black core compound + 0·6% moisture .	55	100

rounded grains; the differences are less marked with some bonds than with others. A further difference, which at present can only be expressed in relative terms, is that found in the friability of the

surfaces of the test-pieces in the laboratory or of cores in the foundry. Provided that the mechanical gradings are comparable, the friability is greater for an angular sand than for one composed of rounded grains. A series of sands with nearly identical gradings but with different coefficients of angularity was bonded with a mixture of linseed oil and semi-solid core compound, made into A.F.A. test-pieces and baked in the usual way. After cooling, the sands were placed in order of increasing surface friability, comparison being made by rubbing the test-pieces between the finger and thumb. The angularity coefficients of the sands used were : 1·05, 1·10, 1·15, 1·20 and 1·30. It was found that the friability increased with the coefficient of angularity.

(c) *Sands with both Clay and Organic Bonds.*

Series of mixes were prepared with the *M*4 and *O* sands, the

TABLE XIII.—*The Moulding Properties of Some* M4 *and* O *Sand Mixes.*

Sand :	*M*4.	*O*.	*M*4.	*O*.
Bond.				
Wyoming bentonite. %	1·0	1·0	...	...
Fulbond No. 4*A*. %	...	...	1·0	1·0
Spermolin *AX*. %	2·4	2·4	2·4	2·4
Spermolin oil. % .	0·8	0·8	0·8	0·8
A.F.A. test-pieces rammed 3 times.				
Bulk density. G. per c.c.	1·60	1·59	1·60	1·59
Green permeability number	420	440	420	420
Green compressive strength. Lb. per sq. in.	1·4	3·2	... *	2·1
Dry permeability number	460	460	...	440
Dry compressive strength. Lb. per sq. in.	330	340	...	295
A.F.A. test-pieces rammed 10 times.				
Bulk density. G. per c.c.	1·67	1·64	1·67	1·64
Green permeability number	300	350	300	350
Green compressive strength. Lb. per sq. in.	1·7	3·9	... *	2·3
Dry permeability number	350	400	...	400
Dry compressive strength. Lb. per sq. in.	395	385	...	395
Tensile strength. Lb. per sq. in.	160	260	150	270

* A.F.A. green compression test-pieces too weak to handle, consequently no dry test-pieces could be prepared.

characteristics of which have already been given in Table VII. and Fig. 7. Typical grains of the two sands are shown in Figs. 45 and 46, and the moulding properties of mixes containing Wyoming bentonite and Fulbond No. 4*A*, together with organic bonds, are given in Table XIII. It will be seen that in the mixes containing bentonite the *M*4 sand gave only half the green compressive strength of the *O* sand; in the Fulbond No. 4*A* mixes, the test-

pieces of the $M4$ sand were too weak to handle, *i.e.*, their green strength was less than 0·8 lb. per sq. in., while those of sand O had at least twice this strength.   The dry strengths of the two bentonite mixes were almost equal.   In both the bentonite and the Fulbond No. $4A$ mixes, the tensile strength of the mixes containing sand $M4$ was about 60% of those containing sand O.   When the number of blows of the rammer was increased from three to ten, the permeability numbers, both green and dry, decreased much more for the $M4$ than for the O sand mixes.

Furthermore, if the surface friabilities are compared, it is found that the test-pieces containing $M4$ sand are much more friable than those containing sand O.

These observations on the moulding properties in the laboratory are in accord with foundry experience with similar mixes.

The moulding properties of the mixes recorded above, whether bonded with clay or an organic bond, or with both, all lead to the same conclusion : For a given mechanical grading a sand composed of angular grains has inferior moulding properties to one composed of rounded grains.

V.—The Distribution of Bulk Density in Moulds and Cores.

The shaping of moulding sand by squeezing, ramming or jolting to form a mould or core involves a type of plastic deformation in which the sand is compacted while being deformed to the shape of the pattern or box. The bulk density is rarely uniform throughout the finished mould or core ; consequently the strength and other properties of the compacted sand will vary through the mould. Thus, in machine-moulding, hydraulic squeezing machines in which the sand is pushed round the pattern are not suitable for deep sections, as there is too great a variation in density from the top to the bottom of the mould.[1]
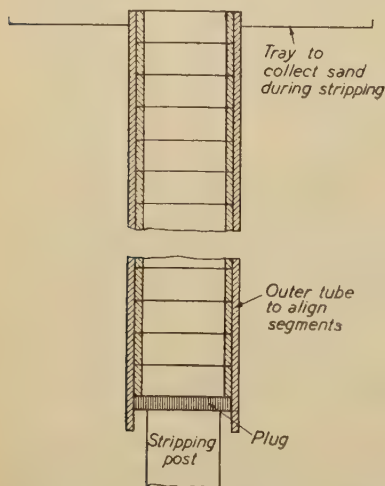
In order to determine the extent of these variations, long cylindrical cores were prepared by squeezing the moulding sand

Fig. 10.—The Bulk-Density Apparatus.

Tray to collect sand during stripping

Outer tube to align segments

Stripping post

Plug

Stripping post

[1] *See* J. Laing and R. T. Rolfe, " A Manual of Foundry Practice," p. 104. London, 1938 : Chapman and Hall, Ltd.

in brass core-boxes constructed in the manner shown in Fig. 10. The box is formed of tube divided into segments of equal thickness; these segments are kept in alignment by an outer tube into which they just slide. The lower end of the box is closed by a plug. In operation, a known weight of the milled moist moulding sand is placed in the core box after aeration; the surface of the sand is smoothed level, and a plunger, which is a loose sliding fit, is inserted in the box. A dead load is placed on the plunger and left on until no further consolidation of the material takes place. The load and plunger are then removed and the core is stripped, one segment at a time; the weight of sand in each segment is determined to 0·1 g. Since the segments have equal volumes, the weight of sand in each segment is a measure of the bulk density. From these data a curve can be plotted to show the bulk density at various depths below the top of the core. The variations in bulk density are considerable. It was found that for a core-box with an internal diameter of 4·2 cm. clay-bonded sand more than 15 cm. below the surface was practically unaffected by the pressure on the top of the sand. In fact, after the sand has once been compressed, the bottom can be removed from the core box and the sand in the lower part will fall out while the sand in the upper part still sustains the pressure.

An Analysis of the Stress Distribution in the Core-Box.

In a dry sand column subject to lateral constraint lateral pressure is developed by a wedge action between the grains as indicated in Fig. 11. The pressure P (in lb. per sq. in.) on the top layer of the grains will be transmitted to the layer below by forces more or less at right angles to the contacts between the grains. These forces are oblique to the axis of the core-box, and the angle they make with the axis will depend on the manner in which the sand grains pack together. These oblique forces can be resolved into two sets of components, one set R perpendicular to the wall of the core-box and the other set passing through the points of contact with the grains in the layer below. If there were no friction between the grains themselves or between the grains and the wall of the core-box, the pressure at the base of the core-box would be the same as that at the top (neglecting the weight of the sand) and the lateral pressure (in lb. per sq. in.) would be equal to the vertical pressure. In other words, the conditions would resemble those in a vessel containing a fluid.

When there is friction between the grains themselves and between the grains and the wall of the core-box, the lateral pressure R at any level is a function ϕ of the vertical pressure p, depending on the method of packing and on the coefficients of friction involved. This relationship may be expressed by : $R = \phi(p)$.

Moist sand, particularly when clay-bonded, tends to adhere to the core-box, that is, surface tension exists at the boundary between the moist sand and the core-box. The actual area of contact

between the two will depend on the lateral pressure.   As the lateral pressure is increased, the grains will readjust themselves so that they are more closely in contact with the core-box, that is, the actual area of contact between the grains and the core-box will increase.   The surface tension, expressed as force per unit area of the core-box, will therefore be greatest at the top of the core-box and least at the bottom.

The existence of wall drag due to friction and surface tension can be demonstrated by placing aerated moist sand in the core-box in equal portions separated by discs of tissue paper, the surface of each portion being smoothed before the disc is placed on it.   After pressure has been applied to the top of the sand, it will be found that each paper disc has been depressed more at its centre than at its periphery owing to the wall drag.

Consider the forces acting on a layer of sand of thickness δx in the core-box at a depth x below the surface of the sand after equilibrium has been attained under a pressure at the top of the sand (Fig. 12).   The pressure p_1 at the top of the layer will differ
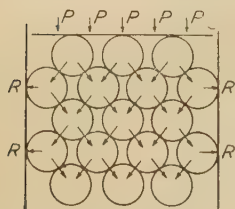
FIG. 11.—The Transmission of Pressure through Sand.
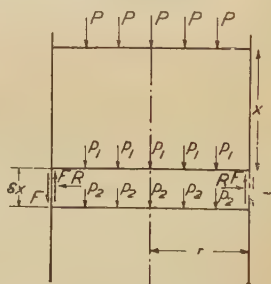
FIG. 12.—The Stress Distribution in the Core-Box.

from the pressure at the base of the layer by the amount of resistance due to the wall drag caused by friction and by surface tension.   The wall drag F, expressed as a force per unit area of the wall of the core-box, is :

$$F = \mu R + \eta R = (\mu + \eta) \cdot \phi(p),$$

where μ is the coefficient of friction and η is a factor relating the lateral pressure R to the surface tension.   Equating the vertical forces :

$$(p_1 - p_2) \cdot \pi \cdot r^2 = 2\pi \cdot r \cdot \delta x (\mu + \eta) \cdot \phi\left(\frac{p_1 + p_2}{2}\right),$$

that is :

$$p_1 - p_2 = 2\frac{\delta x}{r} (\mu + \eta) \cdot \phi\left(\frac{p_1 + p_2}{2}\right).$$

The bulk density to which the sand is compacted is a function f of the pressure to which it has been subjected; that is :

$$\Delta = f(p).$$

The difference in bulk density between the top and bottom of the layer δx will be :

$$\Delta_1 - \Delta_2 = f(p_1 - p_2) = f\left[2\frac{\delta x}{r} \cdot \mu \cdot \phi\left(\frac{p_1 + p}{2}\right)\right],$$

where Δ_1 and Δ_2 are the bulk densities corresponding to p_1 and p_2. Thus, for a given difference in bulk density the ratio of $\delta x/r$ should be constant. In order to verify this point, the variation in bulk density in two core-boxes of different diameters was determined for a number of sand mixes. The curves for bulk density Δ against depth x for one clay-bonded mix are shown in Fig. 13. For the
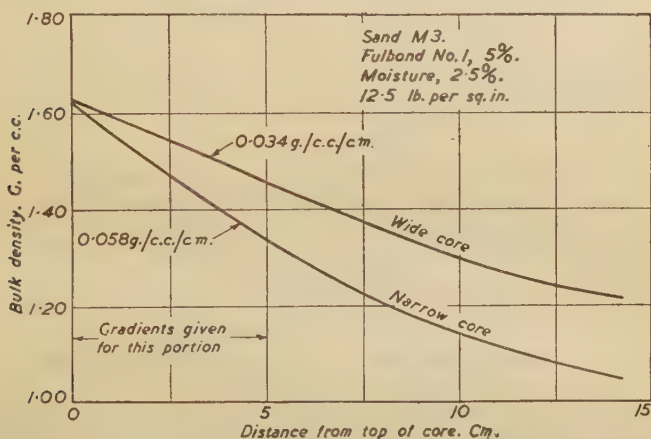
Fig. 13.—Effect of the Diameter of the Core-Box on the Bulk-Density Gradient.

initial portion of each curve the values of δx corresponding to a bulk density difference of 0·20 g. per c.c. are 3·5 cm. and 6·0 cm. for the narrow and wide cores respectively; the diameters of the cores were 4·4 cm. and 7·3 cm. The values of $\delta x/r$ are :

Narrow core, $3\cdot5/4\cdot4 = 0\cdot795$
Wide core, $6\cdot0/7\cdot3 = 0\cdot822$.

The agreement with theory is better than might be expected, as the two core-boxes were made of brass tubes which had been manufactured in different ways. It implies that as the diameter of the core-box is increased, the bulk density variation becomes proportionately less. Differences observed in these core-boxes will also apply on the larger scale in foundry practice.

Some Factors Affecting the Bulk-Density Gradient.

The effect of pressure on the bulk-density gradient is illustrated by Fig. 14. An increase in pressure raises the bulk density down the whole core, but the rate of decrease of bulk density, i.e., the bulk-

density gradient, remains unchanged.   Thus an increase of pressure
does not make the bulk-density distribution more uniform.

In clay-bonded sands, an increase in moisture content reduces
the bulk-density gradient slightly, provided that the moisture
content does not exceed that at which the sand still has appreciable
strength.   An example is shown in Fig. 15.
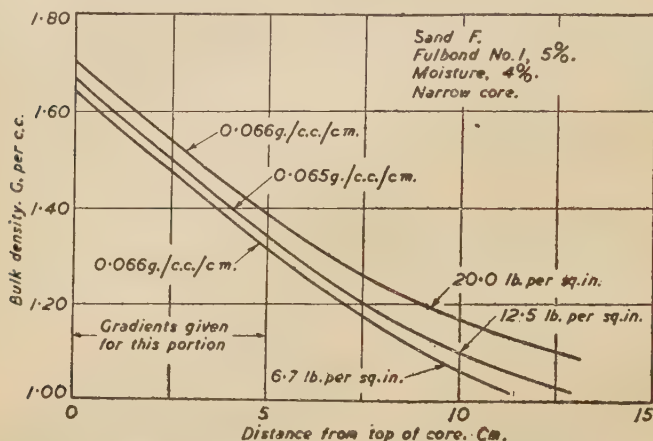
FIG. 14.—Effect of the Pressure on the Bulk-Density Gradient.

The nature of the bond has a marked effect on the bulk-density
gradient.   The gradients for an oil-bonded and a clay-bonded sand
are given in Fig. 16.   The oil-bonded sand packs much more
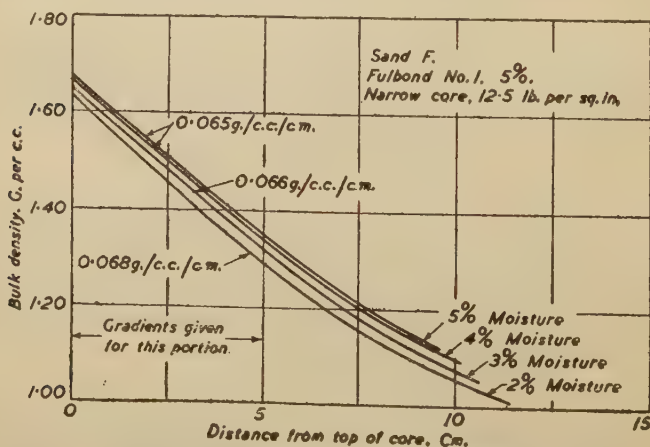
FIG. 15.—Effect of Moisture on the Bulk-Density Gradient.

uniformly than the clay-bonded sand, owing to the better lubricating action of the oil.

The effect of grain shape on the bulk-density gradient is illustrated by Figs. 17 to 20. These gradients are given for mixes the moulding properties of which have already been discussed. In each case the
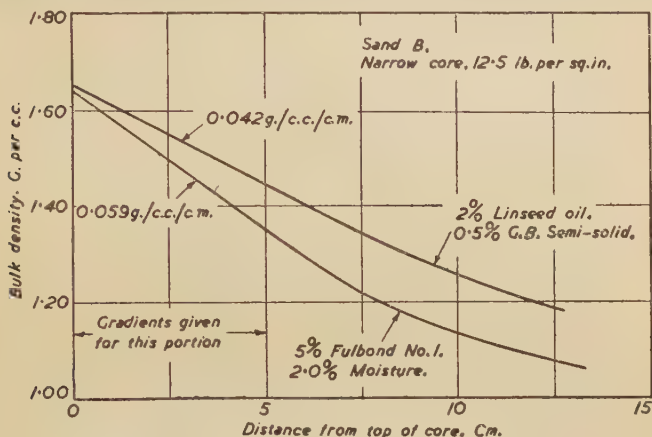
FIG. 16.—Effect of the Bond on the Bulk-Density Gradient.

sands compared have similar mechanical gradings and different coefficients of angularity. The sands with higher coefficients do not pack so uniformly as those with the lower coefficients. These examples are typical of many mixes which have been examined and indicate that this may be a general principle.
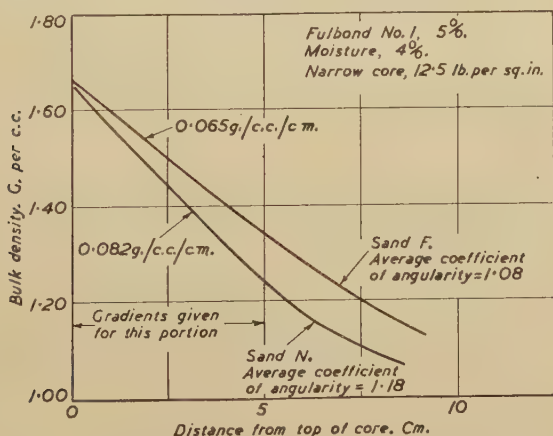
FIG. 17.—Bulk-Density Gradients for Sands *F* and *N*.

The Relation of the Bulk-Density Gradient to the Moulding Properties.

Though squeezing was adopted as a standard basis of comparison, experiments with a small-scale jolting machine showed that mixes containing angular sands did not pack so uniformly as those con-
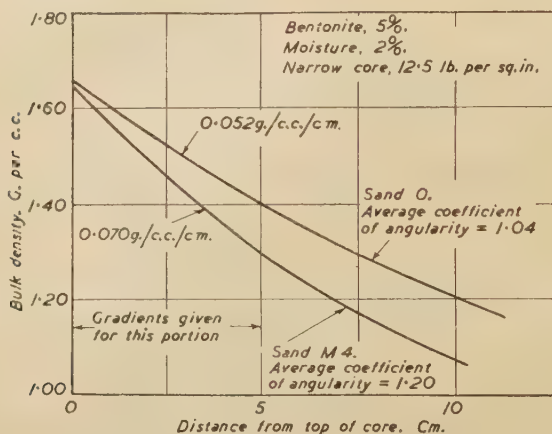
FIG. 18.—Bulk-Density Gradients for Sands M4 and O.
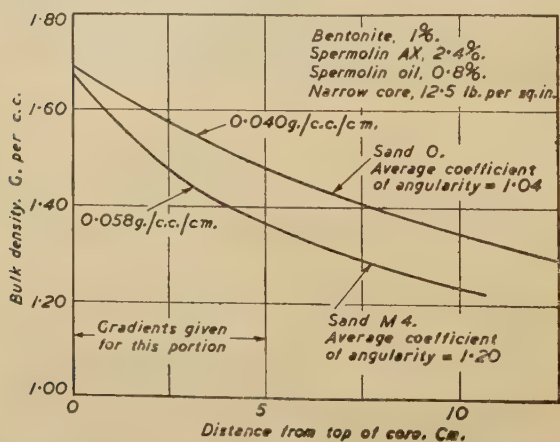
FIG. 19.—Bulk-Density Gradients for Sands M4 and O with Another Bond.

taining rounded sands. The bulk-density gradient may also be applied to moulds and cores prepared by jolting.
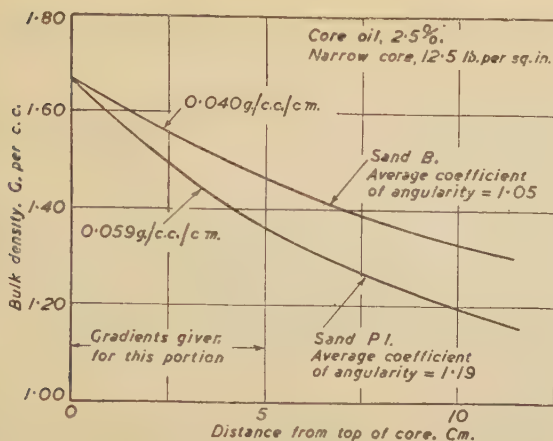
FIG. 20.—Bulk-Density Gradients for Sands *B* and *P*1.

In an A.F.A. test-piece prepared by ramming at one end the bulk density decreases from the top to the bottom of the core, whereas with double-ended ramming the bulk density is highest at the ends and least in the centre. If test-pieces prepared with angular and rounded sands have the same average bulk density, the bulk density at the ends of double-rammed test-pieces prepared with the angular sand will be higher than for the rounded sand, while at the centre the bulk density will be lower for the angular than for the rounded sand. Because the bulk density of the test-piece of the angular sand is lower at the centre than that of the rounded sand, it is to be expected that its strength will be lower.

In the foundry a core prepared with a rounded sand may have sufficient strength to be handled safely in the green state; but one prepared in the same way with an angular sand will show a bigger variation in bulk density, so that the bulk density and, therefore, the green strength of some parts of the core will be too low for safe handling.

The bulk-density distribution does not provide a complete solution of the differences in moulding properties. For instance, *M*4 and *M*3 sands when similarly bonded give almost identical bulk-density gradients, but the *M*3 sand gives a higher green strength (*see* Table XIV. below). The characteristics of the two sands are included in Table III. It will be seen that the two sands have practically the same average coefficients of angularity but the *M*3 sand is not quite so well graded as *M*4. Differences such as these are due to the difference in the grain-size distribution.

VI.—Intergranular Structures in Angular and Rounded
Sands.

The intergranular structures in sands depend on the mechanical
grading, the grain shape, the roughness of the grain surfaces and
the nature of the bond.

The structures can conveniently be discussed by reference to
the sands O and $M4$, the characteristics of which are recorded in
Table VII. and Fig. 7.   The O sand is composed of rounded grains;
when mixes containing this sand are rammed, the grain relations
will be similar to those indicated in Fig 21 (a).   Because the grain
size is nearly uniform and the grains are nearly spherical, the grain
junctions will all be similar; the cross-sectional areas A of the bond
at each grain will be nearly the same, that is, the junctions will be
equally strong.

When $M4$ sand mixes are rammed, two types of grain contact are
possible.   The flats of two grains may be in contact as in Fig. 21 (b),

(a) Sand O.   (b) Sand M4.   (c) Sand M4,
                  Flat - to - flat.   Angle - to - flat.
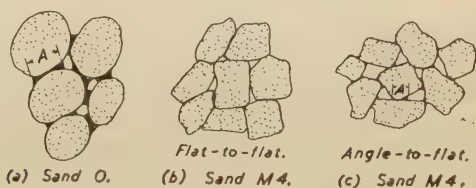
Fig. 21.—Grain Relationships.

so forming a junction at least as strong as those in the O sand.
Alternatively, the angle of one grain may rest against the flat of the
adjacent grains; the cross-sectional area A of the bond in this case
will be much less than that of the junctions in the O sand.   Junctions
of the angle-to-flat type must be at least as common as those of the
flat-to-flat type or else the permeability of the $M4$ test-pieces would
be much lower than that of the O test-pieces (see Table XIII.).
The strength of the $M4$ test-pieces is determined by these angle-to-
flat junctions rather than by the flat-to-flat junctions.

The tensile strengths when these sands are oil-bonded will be
determined by the relative cross-sectional areas A in Fig. 21, (a) and
(c).   The dry compressive strengths will be determined partly by
the cross-sectional areas A and partly by the extent to which the
angles of the grains fit into the roughnesses in the adjacent grains;
these two factors are compensating, and, as a result, the dry strengths
of the two sands do not show the marked differences seen in the
tensile strengths.

The green compressive strengths depend on the same factors
as the dry compressive strengths and, in addition, on the lubricating
action of the bond.   This lubricating action minimises the friction

between the grains, so that the cross-sectional area of the bond becomes the most important factor in determining the green strength.

VII.—METHODS OF REDUCING THE EFFECT OF THE GRAIN SHAPE ON THE MOULDING PROPERTIES.

The effect of the grain shape on the moulding properties may be reduced in several ways. If the number of flat-to-flat contacts is increased by making the grading less uniform, the cross-sectional area of the contacts is increased and the strength properties are thereby improved. Table XIV. records the results of tests on sands $M4$ and $M3$ and a mixture of $M4$ with the finer sand $M1$ (*see* Table III.). The $M3$ sand and the mixture are not so well-graded as the $M4$ sand.

TABLE XIV.—THE MOULDING PROPERTIES OF SOME ANGULAR SANDS.

Sand :	$M3$.	$M4$	75% $M4$, 25% $M1$.
Bond.			
Wyoming bentonite. %	1·0	1·0	1·0
Spermolin AX. %	2·4	2·4	2·4
Spermolin oil. %	0·8	0·8	0·8
A.F.A. test-pieces rammed 3 times.			
Bulk density. G. per c.c.	1·60	1·60	1·58
Green permeability number	420	420	230
Green compressive strength. Lb. per sq. in.	2·1	1·4	1·8
Dry permeability number	440	460	262
Dry compressive strength. Lb. per sq. in.	350	330	550
A.F.A. test-pieces rammed 10 times.			
Bulk density. G. per c.c.	1·65	1·67	1·64
Green permeability number	285	300	191
Green compressive strength. Lb. per sq. in.	2·9	1·7	2·4
Dry permeability number	380	350	230
Dry compressive strength. Lb. per sq. in.	480	395	680
Tensile strength. Lb. per sq. in.	210	160	205

Though the strength properties are improved, the bulk-density gradient remains practically unchanged. The figures for narrow cores of these mixes are :

Sand $M3$.	0·060 g. per c.c. per cm.	
Sand $M4$.	0·058 ,, ,, ,,	
Mixture of sands $M4$ and $M1$	0·060 ,, ,, ,,	

The bulk-density gradient can be reduced by a suitable choice of bond. This is illustrated by a comparison of Figs. 18 and 19.

The strength properties can be improved by altering the type and proportion of bond. An example is given in Table XV.

TABLE XV.—*The Moulding Properties of Two* M4 *Sand Mixes.*

Bond.		
Wyoming bentonite. %	1·0	...
Spermolin *AX*. %	2·4	...
Spermolin oil. %	0·8	1·25
N.A. ball clay. %	...	3·5
G.B. Kordek. %	...	2·5
Moisture. %	...	4·0
A.F.A. test-pieces rammed 3 times.		
Bulk density. G. per c.c.	1·60	1·60
Green permeability number	420	260
Green compressive strength. Lb. per sq. in.	1·4	2·4
Dry permeability number	460	320
Dry compressive strength. Lb. per sq. in.	330	350
A.F.A. test-pieces rammed 10 times.		
Bulk density. G. per c.c.	1·67	1·66
Green permeability number	300	170
Green compressive strength. Lb. per sq. in.	1·7	3·3
Dry permeability number	350	191
Dry compressive strength. Lb. per sq. in.	395	542

VIII.—CONCLUSIONS.

The use of sands composed of angular grains in place of sands composed of rounded grains has several disadvantages. For sands having comparable mechanical gradings it is found that :

(1) In clay-bonded mixes, the green and dry strengths for the angular sands are considerably lower than those for the rounded sands.

(2) In oil-bonded mixes, the tensile strengths for the angular sands are much lower than those for the rounded sands.

(3) In mixes bonded with both clay and oil, the green and tensile strengths are much lower for the angular sands than for the rounded sands.

(4) When the mixes are made into long cylindrical cores by squeezing, the angular sands do not pack so uniformly as the rounded sands, that is, the bulk-density gradient is greater for the angular than for the rounded sands.

(5) Test-pieces of angular sands do not strip so easily as those of rounded sands. Their surface friability after baking increases as the angularity of the grains increases.

Thus the angular sands have moulding properties inferior to those of the rounded sands, which is due partly to their greater bulk-density gradients and partly to the difference in grain relationships.

The differences in strength are due primarily to grain shape and not to specific surface. If bond is added to two similarly graded sands in proportion to their specific surfaces the more angular sand will still have a much lower strength than the more rounded sand.

The effect of grain shape may be minimised in several ways. The strength properties of the angular sands can be improved if their grading is widened. The bulk-density gradient can be reduced by a suitable choice of bond. Finally, an alteration in the type and proportion of bond may improve both the strength properties and the bulk-density gradient.

THE BONDING PROPERTIES OF MIXTURES OF PETROLEUM EXTRACTS AND LINSEED OIL AND OF THE EXTRACTS THEMSELVES.[1]

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Paper No. 9/1944 of the Steel Castings Research Committee (submitted by the Moulding Materials Sub-Committee).

SUMMARY.

The results obtained in this investigation show that petroleum extracts, produced at refineries in Great Britain as a by-product in the purification of the lubricating-oil fraction from the distillation of crude petroleum, can be used satisfactorily to replace at least 40% of the linseed oil in core-sand mixtures. This replacement is advantageous economically, as the petroleum extracts are at present much lower in price than linseed oil, and there is the additional advantage of utilising a home-produced by-product.

Complete replacement of linseed oil by petroleum extract was unsatisfactory in the series of tests made.

Foreword.

FOLLOWING correspondence with the Ministry of Supply, Foundry Bonding Materials Control, and Mr. K. Headlam-Morley, at that time Deputy Controller, the bulk samples of the " Pool " aromatic extracts used in the experimental work described herein were supplied by Mr. H. Cunliffe of The Petroleum Board. The experimental work described in this paper was carried out in the Department of Refractory Materials, Sheffield University, with assistance from Mr. E. S. Squire and Mr. W. Taylor of The Petroleum Board technical staff.

A number of tests with these extracts has been made also by Mr. T. R. Walker, English Steel Corporation, Ltd., and a report on these is submitted in Addendum I. to this paper. Two further extracts, supplied after the main investigation had been completed, are briefly reported on in Addendum II.

(a) *Introduction.*

The last fraction usually separated in the distillation of petroleum is rich in lubricating oil. This fraction is treated with solvents,

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such as liquid sulphur dioxide, furfural and cresol plus propane, in
order to remove the less paraffinic constituents. The dissolved
material is then recovered by evaporating the solvent. The extracts
examined are listed in Table I.; they are produced on a commercial
scale from the lubricating-oil fractions of crude oils from several
sources, using different solvents. Substantial quantities of these
extracts, uniform in composition, are produced. Sufficient would
be available from normal production for foundry use.

TABLE I.—*The Petroleum Extracts Examined.*

Grade of Extract.						Viscosity. (Redwood I. at 140° F.)	Sp. Gr.
Group 1(2241)	.	.	.	.	.	190	1·002
Group 1(P.B.3)	.	.	.	.	.	153	0·975
Group 1A(140)	. .	.	.	.	.	140	0·974
Group 1(72)	.	.	.	.	.	660	1·04
Group 3(105)	.	.	.	.	.	3270	1·06
Mixture (50/50) of Groups 1(72) and 3(105)					·{	(Probably) ~1900	} ...
Group 1(P.B.7)	.	.	.	.	.	175	1·00

Group 1A(140) is obtained from Group 1(P.B.3) by special
treatment and is used in certain manufactured products. Group
3(105) is the residue left when Group 1(72) is subjected to dis-
tillation; the two are generally similar in composition but Group
3(105) has a higher molecular weight.

The extracts differ considerably in viscosity. At room tem-
perature Group 3(105) is more viscous and Group 1(72) rather
less viscous than most semi-solid core compounds; the viscosity of
the 50/50 mixture of these two grades is comparable with that of a
semi-solid core compound. Groups 1(2241), 1(P.B.3), 1A(140)
and 1(P.B.7) are not quite so fluid as raw linseed oil.

(b) *The Determination of the Bonding Properties.*

The bonding properties were determined by means of mixes
prepared from silica sands bonded with the extracts, either alone
or in conjunction with other bonds. (In the following, all mix
compositions are expressed as percentages by weight.) Chelford
sand was employed in most of the mixes, and Leighton Buzzard
(Arnold's No. 52) sand in the remaining ones. Both these sands
are used extensively in core-making. Their characteristics are
given in Table II.

In the initial work, the mixes were prepared in a Simpson-type
motor-driven mill. It was difficult to incorporate the more viscous
extracts. However, it was found that they could be incorporated
satisfactorily in a hand-mill having a different milling mechanism.
This hand-mill was employed in all the tests recorded in this paper.

All the mixes, except those with extracts alone, were subjected to 400 revolutions at 50 r.p.m. and hand-mixed at frequent intervals during the milling; the mixes with the extracts alone were milled until they appeared to be uniform in texture so that comparisons could be drawn between their ease of incorporation.

Linseed oil and many of the extract/linseed-oil mixes were too weak in the green state to make A.F.A. compression test-pieces, so that strength comparisons of these mixes were restricted to dry tensile strengths.

TABLE II.—*The Characteristics of the Silica Sands Used.*

	Sand :	Chelford.	Leighton Buzzard.
Mechanical grading.			
B.S.I. Sieve No.			
On 5. %		0·0	0·0
„ 8. %		0·0	0·1
„ 10. %		0·0	0·1
„ 16. %		0·2	0·1
„ 22. %		0·4	0·1
„ 30. %		3·7	6·2
„ 44. %		18·4	34·8
„ 60. %		32·1	40·4
„ 72. %		19·0	12·3
„ 100. %		17·9	5·5
„ 150. %		5·1	0·3
Thro' 150. %		3·2	0·1
Total. %		100·0	100·0
Specific surface. Sq. cm. per g.		125·6	57·2
Average coefficient of angularity		1·09	1·06
Chemical analyses.			
SiO_2. %		97·16	98·75
TiO_2. %		0·02	0·02
Fe_2O_3. %		0·15	0·16
Al_2O_3. %		1·46	0·47
CaO. %		0·14	0·12
MgO. %		0·18	0·08
Alkali as K_2O. %		0·38	0·14
Loss on ignition. %		0·45	0·20
Total. %		99·94	99·94

With the exception of the tests made on the effect of drying time and temperature, all the test-pieces were dried at 200° C. for 2 hr. and tested when cool.

(c) *The Bonding Properties of Petroleum-Extract/Linseed-Oil Mixtures.*

In the tests described in this section Chelford sand was bonded with both extract and linseed oil, in different ratios, the total

proportion of bond being maintained at 2%. For the majority of these tests, the linseed oil was mixed with the sand first and then the extract was added. Tests were also made in which the extract was mixed with the linseed oil before addition to the sand. The effect of this premixing is illustrated by the results obtained on four A.F.A. tensile test-pieces rammed 3 times and dried for 2 hr. at 200° C., the bond being in each case 1% of linseed oil plus 1% of Group 1(72) extract :

		Dry Tensile Strength.			Lb. per sq. in.	
Linseed oil { added separately	392	402	360	378	Av. 382
and extract { premixed	391	390	382	392	Av. 389

The above tests indicate little or no advantage from premixing, except that there is the expected tendency to a quicker development of a uniform mix. The oil was added to the sand before the extract

TABLE III.—*The Dry Tensile Strength of Chelford Sand Bonded with Various Proportions of Petroleum Extract and Linseed Oil (in lb. per sq. in.).*

A.F.A. tensile test-pieces; rammed 3 times; dried at 200° C. for 2 hr.

Chelford sand. Parts .	100	100	100	100	100	100	100
Linseed oil. Parts .	2·0	1·6	1·2	1·0	0·8	0·4	0·0
Extract. Parts .	0·0	0·4	0·8	1·0	1·2	1·6	2·0
Group 1(2241) .	392	387	376	274	241	79	22
Group 1(P.B.3) .	392	382	368	320	201	45	18
Group 1A(140) .	392	362	335	249	236	76	13
Group 1(72) .	392	399	362	386	271	109	12
Group 3(105) .	392	407	388	343	311	111	27
Group 1(P.B.7) .	392	397	400	274	237	25	22

in the tests recorded in Table III., as this procedure is more likely to be adopted in foundry practice than premixing.
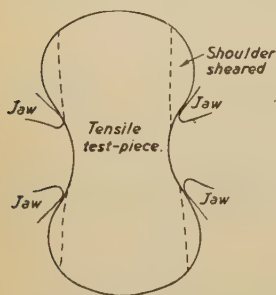
FIG. 1.—The Failure of Tensile Test-Pieces containing a High Proportion of Petroleum Extract.

For mixes containing up to 1·2% of extract, the surfaces of the test-pieces were as firm as with a bond composed of linseed oil only. If the proportion of extract was increased beyond 1·2%, the test-pieces developed friable surfaces. As a consequence, the test-pieces tended to shear in the jaws instead of fracturing at the smallest section, as shown in Fig. 1. For a given ratio of linseed oil to extract no difference could be detected in the surface friability with different extracts. Mixes containing Group 1(72) and Group 3(105) extracts had rather

more green strength than those with linseed oil and were rather easier to strip.

Curves relating the dry tensile strengths given in Table III. to
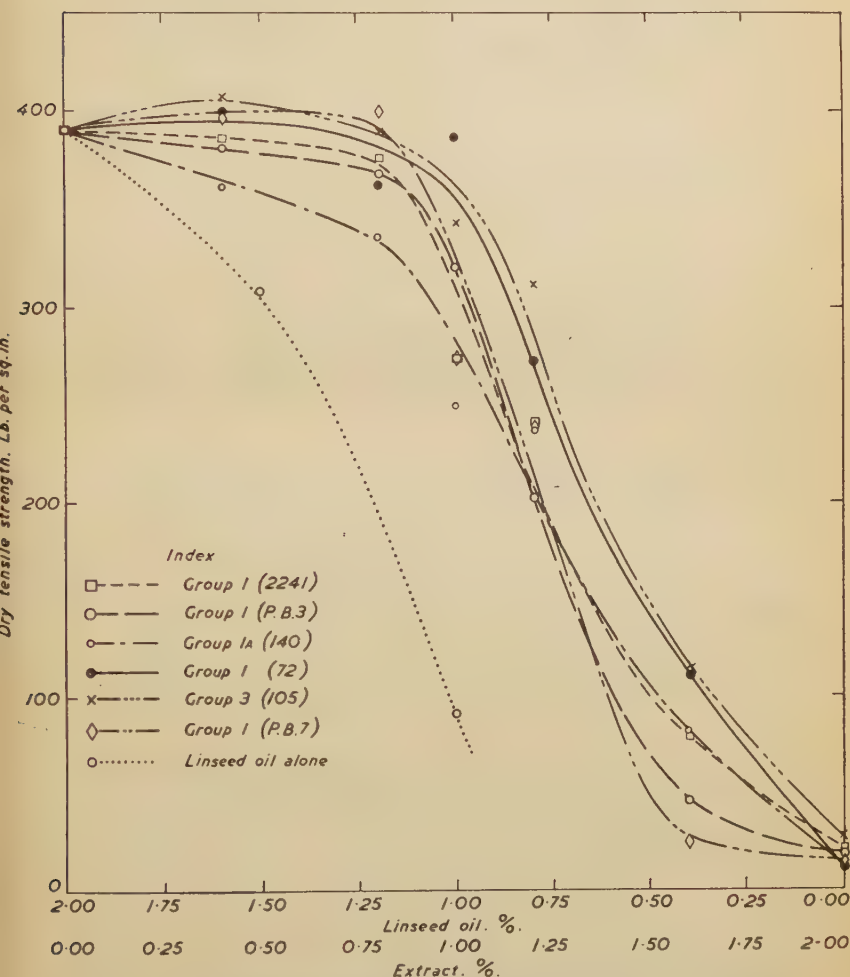
FIG. 2.—The Dry Tensile Strength of Chelford Sand Bonded with Linseed Oil and Various Petroleum Extracts.

the extract/linseed-oil ratio for the different extracts are shown in Fig. 2. They indicate that, except with Group 1A(140), the dry tensile strength remains almost constant as linseed oil is replaced by extract until 40% of the oil in the bond has been replaced;

thereafter the tensile strength decreases sharply as the proportion of extract is increased. Apart from Group 1A(140), the differences observed in the range 0·0–0·8% of extract are almost within the limits of experimental error. In the range 0·8–2·0% of extract the tensile strength for Group 1(72) and Group 3(105) falls off rather less sharply than for the other extracts. The curve for Group 1A(140) shows that the tensile strength decreases slowly until 40% of the linseed oil is replaced and thereafter much more sharply.

Fig. 2 also includes the curve for various proportions of linseed oil without the addition of extract. It will be seen that the addition of extract increases the dry tensile strength decidedly.

Tests were also made with Arnold's No. 52 (Leighton Buzzard) sand in which the linseed oil and extract were premixed. The dry tensile strengths are recorded in Table IV. It will be seen that with this sand the replacement of part of the linseed oil by extract improved the dry tensile strength slightly. The surfaces of the test-pieces of all the mixes recorded in Table IV. were equally firm, just as was observed with Chelford sand similarly bonded.

TABLE IV.—*The Dry Tensile Strength of Arnold's No. 52 Sand Bonded with Petroleum Extract and Linseed Oil.*

A.F.A. tensile test-pieces; rammed 3 times; dried at 200° C. for 2 hr.

Arnold's No. 52 sand. Parts . . .	100	100	100	100	100
Linseed oil. Parts	2·0	1·6	1·2	1·0	0·8
Group 1(72). Parts.	0·0	0·4	0·8	1·0	1·2
Tensile strength. Lb. per sq. in.	400	455	441	397	310

The Effect of Driers.—An addition of 1·67% of cobalt naphthenate—that is, 0·2% of cobalt—was made to the extract used in some of the extract/linseed-oil mixes. With this naphthenate addition a dry tensile strength of 330 lb. per sq. in. was obtained on a Chelford sand test-piece bonded with 1% of linseed oil plus 1% of Group 1(72) extract and rammed 3 times and dried for 2 hr. at 200° C., as compared to 386 lb. per sq. in. in the absence of naphthenate. There was thus a small decrease in strength. Possibly the naphthenate accelerated the drying of the linseed oil so much that it not only dried but started to decompose.

The Effect of the Drying Temperature and Time.—The results recorded in Table V. suggest that drying at 200° C. for 2 hr. gives the best results with extract/linseed-oil mixtures, and that the drying conditions for the optimum tensile strength of the extract/linseed-oil mixes may be a little more critical than for mixes with linseed oil alone, but the difference is probably small. The surfaces

of all the test-pieces the tensile strengths of which are given in Table V. were quite firm.   (*See* Addendum III.)

TABLE V.—*The Effect of the Drying Temperature and Time on the Dry Tensile Strength of Chelford Sand Bonded with Petroleum Extract and Linseed Oil and with Linseed Oil Alone.*

Rammed 3 times.

Drying Temperature. °C.	Tensile Strength (lb. per sq. in.) after Drying for—			
	1½ hr.	2 hr.	2½ hr.	3 hr.
	Bonded with 1% of Linseed Oil plus 1% of Group 1(72) Extract.			
175	324	340	291	299
200	339	386	315	...
225	267	249	...	...
	Bonded with 2% of Linseed Oil.			
175	299	300	280	296
200	330	390	370	...
225	239	250	...	...

The Effect of the Petroleum-Extract/Linseed-Oil Ratio on the Dry Tensile Strength.—In view of the promising results obtained with extract/linseed-oil mixtures, further tests were made in order to determine the relation of the extract/linseed-oil ratio to the tensile strength of Chelford and Leighton Buzzard sand mixes.   The extract and linseed oil were mixed before addition to the sand. The results are recorded in Table VI. and Fig. 3.   For a given

TABLE VI.—*The Dry Tensile Strength (in lb. per sq. in.) of Chelford and Arnold's No. 52 (Leighton Buzzard) Sand Bonded with Various Petroleum-Extract/Linseed-Oil Mixtures.*

Subjected to 400 revolutions in hand-mill; rammed 3 times; dried for 2 hr. at 200° C.

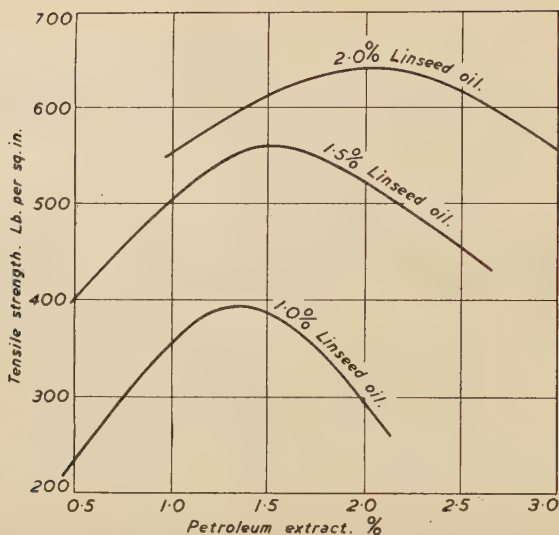| Linseed Oil. %.	Group 1(72) Extract—									
	0·33%.	0·50%.	0·67%.	0·75%.	1·00%.	1·50%.	1·67%.	2·00%.	2·50%.	3·00%.
	Chelford Sand.									
0·75	...	...	...	200	...	...	...	...	...	...
1·00	...	234	...	238	355	386	...	290	...	...
1·50	...	390	...	476	488	560	...	...	453	...
2·00	...	...	...	...	572	...	...	648	...	553
	Arnold's No. 52 (Leighton Buzzard) Sand.									
0·67	220	...	...	...	...	...	...	...	...	...
1·00	...	300	...	...	...	...	...	...	...	...
1·33	...	...	440	...	...	...	...	...	...	...
2·00	...	...	...	...	485	...	...	...	...	...
2·33	...	...	...	...	...	...	530	...	...	...

FIG. 3.—The Dry Tensile Strength of Chelford Sand Bonded with 1·0%, 1·5% and 2% of Linseed Oil and various Proportions of Group 1(72) Petroleum Extract.
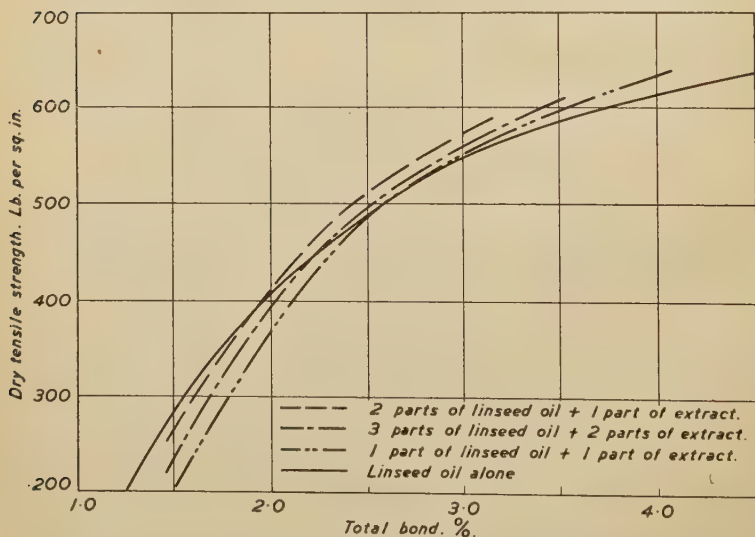

FIG. 4.—The Dry Tensile Strength of Chelford Sand Bonded with Group 1(72) Petroleum Extract and Linseed Oil.

content of linseed oil, they indicate that there is an optimum addition of extract which will give the highest tensile strength. This optimum addition is slightly more critical with 1% of linseed oil than with 2%.

The Effect of the Proportion of Bond on the Dry Tensile Strength.— The tensile strengths of Chelford sand and Leighton Buzzard sand bonded with various proportions of linseed oil are given in Table VII. and in Figs. 4 and 5, respectively. Included in these diagrams are

TABLE VII.—*The Dry Tensile Strength of Chelford and Leighton Buzzard Sands Bonded with Linseed Oil.*

Subjected to 400 revolutions in hand-mill; rammed 3 times; dried at 200° C. for 2 hr.

Linseed Oil. %.	Dry Tensile Strength. Lb. per sq in.	
	Chelford Sand.	Leighton Buzzard Sand.
1·0	90	202
1·5	309	388
2·0	390	399
2·5	495	...
3·0	549	528
4·0	634	558
5·0	626	...
6·0	686	...

smoothed curves indicating the tensile strengths in relation to bond percentage for various extract/linseed-oil ratios; these curves are based on the data given in Table VI.
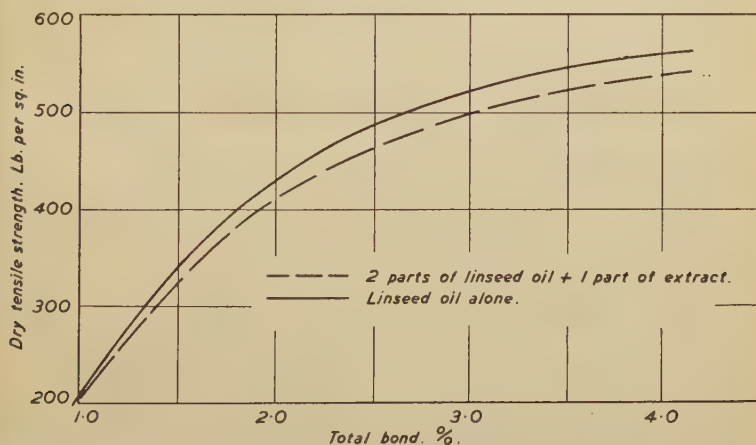

FIG. 5.—The Dry Tensile Strength of Arnold's 52 Sand (Leighton Buzzard) Bonded with Group 1(72) Petroleum Extract and Linseed Oil.

(d) *The Bonding Properties of Petroleum-Extract/Linseed-Oil Mixtures in Conjunction with Other Organic Binders.*

Tests were made with extract/linseed-oil mixtures in conjunction with other organic binders in order to determine whether the partial replacement of linseed oil by extract affected the bonding properties.

(i) *Mixes bonded with Linseed Oil and Molasses.*—The replacement of 50% of the linseed oil by extract resulted in a slight improvement in green strength but lowered the dry compressive and dry tensile strengths, as will be seen from the data recorded in Table VIII. The dry test-pieces made with the linseed-oil/molasses mixture were fairly firm, while those containing extract, linseed oil and molasses were slightly friable. In view of these differences, mixtures slightly richer in linseed oil were used in some of the subsequent tests. Mixes in which all the linseed oil was replaced by extract are included for comparison; their dry strengths were unsatisfactory and the surfaces of dried test-pieces were very friable.

TABLE VIII.—*The Bonding Properties of Petroleum Extract and Linseed Oil in Conjunction with Molasses.*

Chelford sand; 400 revolutions in hand-mill; dried at 200° C. for 2 hr.

Composition of mixes.					
Chelford sand. Parts	100	100	100	100	100
Molasses. Parts	2·0	2·0	2·0	2·0	2·0
Linseed oil. Parts	1·0	0·5	0·5	...	...
Group 1(P.B.3). Parts	...	0·5	...	1·0	...
Group 1(72). Parts	...	...	0·5	...	1·0
A.F.A. compression test-pieces rammed 3 times.					
Green compressive strength. Lb. per sq. in.	2·0	2·4	2·7	2·3	2·4
Dry compressive strength. Lb. per sq. in.	740	600	620	36	31
A.F.A. compression test-pieces rammed 10 times.					
Green compressive strength. Lb. per sq. in.	2·9	3·8	3·8	3·2	3·3
Dry compressive strength. Lb. per sq. in.	1065	785	860	49	88
A.F.A. tensile test-pieces rammed 3 times.					
Dry tensile strength. Lb. per sq. in.	205	123	125	0	0

(ii) *Stiff Core Creams.*—The results of the tests with stiff core creams are recorded in Table IX. They show that the replacement of 40-50% of the linseed oil by extract improved the green strength slightly and reduced the dry strength slightly. The total replacement of linseed oil by extract gave very low dry strength. No

difference could be detected in the surface friability of dry test-pieces of mixes with linseed oil alone and those in which 40–50% of the linseed oil had been replaced by extract. The surfaces of dry test-pieces in which the linseed oil had been totally replaced were very friable.

TABLE IX.—*The Bonding Properties of Stiff Core Creams Containing Petroleum Extract and Linseed Oil.*

Chelford sand with 3% of stiff cream; 400 revolutions in hand-mill; dried at 200° C. for 2 hr.

Composition of stiff cream.				
Standard Kordek (dextrin). % .	40·0	40·0	40·0	40·0
Linseed oil. %	25·0	15·0	12·5	...
Group 1(72). %	...	10·0	12·5	25·0
Water. %	35·0	35·0	35·0	35·0
A.F.A. compression test-pieces) rammed 3 times.				
Green compressive strength. Lb. per sq. in.	1·6	2·2	2·1	2·5
Dry compressive strength. Lb. per sq. in.	1220	975	850	159
A.F.A. compression test-pieces rammed 10 times.				
Green compressive strength. Lb. per sq. in.	2·1	3·0	2·9	3·5
Dry compressive strength. Lb. per sq. in.	1290	1230	1190	187
A.F.A. tensile test-pieces rammed 3 times.				
Dry tensile strength. Lb. per sq. in. .	236	205	196	25

(iii) *Thin Core Creams.*—The results of the tests with thin core creams are recorded in Table X. The replacement of 40–50% of the linseed oil by extract lowered the green strength very slightly; the dry compressive strength decreased markedly but the dry tensile strength decreased slightly. The surfaces of the dry test-pieces were equally firm.

(iv) *Semi-Solid Core Compounds.*—The results of the tests with semi-solid core compounds are recorded in Table XI. It was found that with these compounds the addition of 0·5% of water was necessary to produce a uniform mix with good moulding properties. It will be seen that the replacement of 40–50% of the linseed oil by the extract improved the green strength slightly, and reduced the dry strength slightly. No change in surface friability could be detected as a consequence of the replacement.

(v) *Mixes bonded with Linseed Oil and G.B. Kordek.*—The replacement of 50% of the linseed oil by extract in mixes containing G.B. Kordek had little effect on the dry compressive strength, though there was a small improvement in green strength (*see* Table XII.). Group 1(72) extract gave a slight increase in dry tensile

strength. The surfaces of the test-pieces containing extract were
as firm as those without extract.

(e) *The Bonding Properties of a Petroleum-Extract/Linseed-Oil
Mixture in Conjunction with Dextrin and Fulbond.*

The purpose of the tests recorded in Table XIII. was to deter-
mine whether extract could be used satisfactorily in the presence

TABLE X.—*The Bonding Properties of Thin Core Creams
Containing Petroleum Extract and Linseed Oil.*

Chelford sand with 3% of thin cream; 400 revolutions in hand-mill; dried
at 200° C. for 2 hr.

Composition of thin cream.			
Standard Kordek (dextrin). % . . .	30·0	30·0	30·0
Linseed oil. %	15·0	9·0	7·5
Group 1(72). %	...	6·0	7·5
Sulphite lye. %	25·0	25·0	25·0
Water. %	30·0	30·0	30·0
A.F.A. compression test-pieces rammed 3 times.			
Green compressive strength. Lb. per sq. in. .	3·2	3·1	2·9
Dry compressive strength. Lb. per sq. in. .	610	477	453
A.F.A. compression test-pieces rammed 10 times.			
Green compressive strength. Lb. per sq. in. .	4·4	4·3	4·0
Dry compressive strength. Lb. per sq. in. .	860	497	462
A.F.A. tensile test-pieces rammed 3 times.			
Dry tensile strength. Lb. per sq. in. . .	134	116	117

TABLE XI.—*The Bonding Properties of Semi-Solid Core
Compounds Containing Petroleum Extract and Linseed Oil.*

Subjected to 400 revolutions in hand-mill; dried at 200° C. for 2 hr. Com-
position of the mix : 100 parts of Chelford sand + 3·0 parts of semi-
solid core compound + 0·5 part of water (added after 300 revolutions).

Composition of the semi-solid core compound.			
Standard Kordek (dextrin). % . . .	50·0	50·0	50·0
Linseed oil. %	20·0	12·0	10·0
Group 1(72). %	...	8·0	10·0
Sulphite lye. %	10·0	10·0	10·0
Water. %	20·0	20·0	20·0
A.F.A. compression test-pieces rammed 3 times.			
Green compressive strength. Lb. per sq. in. .	2·9	3·1	3·4
Dry compressive strength. Lb. per sq. in. .	870	834	750
A.F.A. compression test-pieces rammed 10 times.			
Green compressive strength. Lb. per sq. in. .	4·3	4·4	5·4
Dry compressive strength. Lb. per sq. in. .	1110	875	871
A.F.A. tensile test-pieces rammed 3 times.			
Dry tensile strength. Lb. per sq. in. . .	158	142	151

TABLE XII.—*The Bonding Properties of Petroleum Extract and Linseed Oil in Conjunction with G.B. Kordek.*

Subjected to 400 revolutions in hand-mill; dried at 200° C. for 2 hr.

Composition of mixes.			
Chelford sand. Parts .	100	100	100
G.B. Kordek (starch). Parts	1·0	1·0	1·0
Linseed oil. Parts	2·0	1·0	1·0
Group 1(72). Parts	...	1·0	...
Group 1(P.B.3). Parts	...	...	1·0
Water. Parts	2·7	2·7	2·7
A.F.A. compression test-pieces rammed 3 times.			
Green compressive strength. Lb. per sq. in. .	1·4	1·7	1·6
Dry compressive strength. Lb. per sq. in.	1370	1420	1320
A.F.A. compression test-pieces rammed 10 times.			
Green compressive strength. Lb. per sq. in. .	2·0	2·4	2·1
Dry compressive strength. Lb. per sq. in.	1410	1430	1410
A.F.A. tensile test-pieces rammed 3 times.			
Dry tensile strength. Lb. per sq. in.	248	286	236

of clay. The tests show that extract can replace 50% of the linseed oil quite satisfactorily; there was no difference in surface friability consequent on the use of extract.

TABLE XIII.—*The Bonding Properties of Petroleum Extract and Linseed Oil in Conjunction with Standard Kordek and Fulbond No. 4A.*

Subjected to 400 revolutions in hand-mill; dried at 200° C. for 2 hr.

Composition of mixes.		
Chelford sand. Parts	100	100
Fulbond No. 4A. Parts	2·00	2·00
Standard Kordek. Parts	1·50	1·50
Water. Parts	1·25	1·25
Linseed oil. Parts	1·50	0·75
Group 1(72). Parts .	...	0·75
A.F.A. compression test-pieces rammed 3 times.		
Green permeability No.	233	221
Green compressive strength. Lb. per sq. in.	5·5	5·7
Dry compressive strength. Lb. per sq. in. .	478	478
A.F.A. compression test-pieces rammed 10 times.		
Green permeability No.	150	162
Green compressive strength. Lb. per sq. in.	7·4	7·0
Dry compressive strength. Lb. per sq. in. .	649	625
A.F.A. tensile test-pieces rammed 3 times.		
Dry tensile strength. Lb. per sq. in. .	124	129

(f) *The Bonding Properties of the Petroleum Extracts Alone.*

Chelford sand was the base sand in the tests carried out to study the bonding properties of petroleum extracts alone, and A.F.A. tensile test-pieces rammed three times and dried for 2 hr. at 200° C. were used. The following dry tensile strengths were obtained with additions of 2% of various groups of petroleum extract :

Petroleum extract. Group	1(2241)	1(P.B.3)	1(P.B.7)	1.4(140)	1(72)	3(105)	1(2) + 3(105) (50/50 mixture
Dry tensile strength. Lb. per sq. in.	22	18	22	13	12	27	18

It is seen that the dry tensile strengths were very low compared with that given by the same proportion of raw linseed oil (390 lb. per sq. in.). The linseed-oil test-pieces had firm surfaces after baking. Those prepare' with the extracts were extremely friable on the sides and top, but the under-surfaces, where they had been in contact with the oven shelf, were quite firm. None of the extract test-pieces were soft inside; on the contrary, the interior of the test-pieces (*see* Fig. 6) was nearly as firm as that of a linseed-oil test-piece.
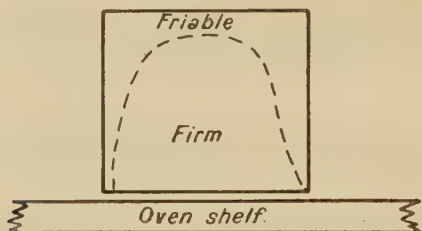

Fig. 6.—Cross-Section of Tensile Test-Piece Bonded with Petroleum Extract.

The mixes with extracts tended to stick to the core-box rather more than those with linseed oil. Those with Group 1(72), Group 3(105) and the 50/50 mixture of these two grades had more green strength than those with the other extracts or raw linseed oil. Mixes with these three extracts required 400 revolutions of the mill before they appeared uniform, whereas those with the other extracts or with linseed oil appeared uniform after 250 revolutions. Further milling did not increase the strength.

The Effect of the Drying Temperature.—After ramming three times, test-pieces containing 2% of Group 1(P.B.3) extract and Group 1(72) extract were dried for 2 hr. at 250° C. instead of 200° C. The dry tensile strength obtained with Group 1(P.B.3) extract was 17 lb. per sq. in. and with Group 1(72) extract 16 lb. per sq. in., as compared to 18 and 12 lb. per sq. in. respectively

after drying at 200° C. The higher drying temperature did not cause any marked improvement in the dry tensile strength. The surface friability of the test-pieces was increased slightly. Linseed-oil mixes dried at 250° C. and tested for comparison showed very variable tensile strengths (between 42 and 170 lb. per sq. in.) owing to the partial decomposition of the bond.

The Effect of the Proportion of Bond.—The proportion of Group 1(72) extract in one of the mixes was increased to 4%. The dry tensile strength obtained with an A.F.A. test-piece rammed 3 times and dried for 3 hr. at 200° C. was 36 lb. per sq. in., as compared with 18 lb. per sq. in. with 2% of extract. Although there was some improvement with the higher proportion of extract, the value obtained was still far below that given by 2% of linseed oil (dried for 2 hr.), which was 390 lb. per sq. in. The surface friability was greatly reduced, but the edges of the test-pieces were still not so firm as those of test-pieces bonded with linseed oil. The 4% extract mixes required 3 hr. to complete the drying.

The Effect of Driers.—Mixes were prepared with extracts containing a small proportion of a drier such as is used to promote the drying of paint or putty. The drier employed was cobalt naphthenate containing about 10% of cobalt. When the extract was treated with 2% of naphthenate, there was some improvement in the dry tensile strength of mixes containing 2% of extract, but, even so, the strength was far less than that of linseed-oil mixes, as will be seen from Table XIV. Extract containing 0·5% of naphthenate

TABLE XIV.—*The Effect of Cobalt Naphthenate Additions on the Dry Tensile Strength of Chelford Sand Bonded with Petroleum Extract.*

A.F.A. tensile test-pieces; rammed 3 times; dried at 200° C. for 2 hr.

Grade of Extract.			Proportion of Extract. %.	Dry Tensile Strength. Lb. per sq. in.	
				With Naphthenate.	Without Naphthenate.
Group 1(P.B.3)	.	.	2	20	18
Group 1(72)	.	.	2	31	12
Group 1(72)	.	.	4	41	36

was employed in mixes containing 4% of extract; the results included in Table XIV. show a slight improvement in dry tensile strength. In all cases the addition of naphthenate did not reduce the surface friability appreciably.

Fumes Evolved During Drying.—When mixes containing the extracts are drying in the oven, they give off more fumes than linseed-oil mixes, but these fumes are not so unpleasant; in particular, they have little effect on the eyes.

(g) *Conclusions.*

(1) In sand mixes bonded with 2% of linseed oil up to 40% of the oil can be replaced by any of the petroleum extracts examined, except Group 1*A*(140) extract, without adversely affecting the tensile strength. If more than 50% of the oil is replaced by extract the tensile strength falls off sharply. Mixtures containing up to 40% of extract require the same milling and drying conditions as those containing linseed oil alone to give the optimum tensile strength. Premixing of the linseed oil and extract before addition to the sand tends to give a more uniform mix.

(2) Up to 50% of the linseed oil in core compounds rich in starch can be replaced by extract; this replacement gives an increase in green strength, without altering the dry strength appreciably.

(3) Up to 40% of the linseed oil in core compounds rich in dextrin can be replaced by extract; this replacement increases the green strength but is accompanied by a slight loss in dry strength.

(4) The replacement of 50% of the linseed oil in core compounds rich in molasses gives an increase in green strength but reduces the dry compressive and tensile strengths; at the same time the surface friability increases slightly.

(5) The replacement of 40-50% of the linseed oil in core compounds rich in sulphite lye reduces the dry compressive and tensile strengths.

(6) Sand mixes bonded with 2% or even 4% of extract give dry tensile strengths far below that of mixes containing 2% of linseed oil. Test-pieces of the extract mixes have extremely friable surfaces. Neither an increase in drying temperature from 200° C. to 250° C. nor the use of driers at 200° C. gives much improvement. From this, it appears unlikely that the extracts could *wholly* replace the linseed oil in mixes containing this bond alone.

(7) The replacement of linseed oil by an extract/linseed-oil mixture containing 40-50% of extract does not alter the stripping qualities of sand mixes.

(8) Of the extracts tested, Group 1(72) gives the best all-round results and its consistency is such that it can be easily handled.

(9) The above conclusions are based on work with Chelford sand, but tests on a number of mixtures with Arnold's 52 (Leighton Buzzard) sand lead to similar conclusions.

Addendum I.

The tests described in the following have been made by **Mr. T. R. Walker, English Steel Corporation, Ltd.** The conclusions to be drawn from them are in general agreement with those of the main paper.

(1) *The Substitution of Part of the Linseed Oil in Core Compounds by Petroleum Extract Group* 1(72).

In the first series of tests the following core compound mixtures were tried out :

No.	Dextrin. G.	Linseed Oil. C.c.	Solid Sul- phite. G.	Water. C.c.	Group 1(72) Extract. C.c.
1	40	25	Nil	35	Nil
2	30	15	17·5	30	Nil
3	50	20	7	20	Nil
4	40	12·5	Nil	35	12·5
5	30	7·5	17·5	30	7·5
6	50	10	7	20	10

The core compound mixtures were prepared as follows :

Nos. 1 *and* 4.—The dextrin was mixed with half the water, then the oil was admixed, and finally the remainder of the water was added and the mass mixed to a cream.

Nos. 2 *and* 5.—The dextrin was dissolved in half the water, and the oil and the sulphite (dissolved in the remaining water) were added and mixed to a cream.

Nos. 3 *and* 6.—The solid sulphite was dissolved in the water and then mixed with the dextrin. Then the oil was added and the mass mixed to a semi-solid state.

On account of a temporary shortage of Chelford sand, the core compounds were placed in air-tight bottles after their preparation and allowed to stand for 24 hr.

Core compounds Nos. 1, 2, 3, 4, 5 and 6 respectively were incorporated in sand mixtures *A, B, C, D, E* and *F*. These sand mixtures were prepared in the following way :

The core compound (45 g., *i.e.*, 3%) was added to 1500 g. of Chelford silica sand and the mixture milled with 10 c.c. of water.   Mixtures *A, B, D* and *E* were milled for 10 min. before the addition of water, after which they were milled for a further 5 min.   Mixtures *C* and *F* were milled for 5 min. before the addition of the water, and another 5 min. after the addition.

Mixtures *A, B, D, E* and *F* had an oily, silky feel, whilst mixture *C* had no flowability.   All dried samples had good hard faces and were of an even colour throughout.

The results of a number of tests on the sand mixtures are given in Table XV.

(2) *The Effect of Various Petroleum Extracts in Sand Mixtures free from Linseed Oil but containing G.B. Kordek.*

In the second series of tests the effect was studied of the petroleum extracts examined in the main paper on mixes free from linseed oil but containing G.B. Kordek.   Each mixture

TABLE XV.—*The Properties of Sand Mixtures* A, B, C, D, E *and* F.*

Sand mixture : Weight of core. G.:	A. 165 (170)	B. 170 (170)	C. 160 (170)	D. 170 (170)	E. 170 (170)	F. 170 (170)
Permeability No.	193 (150)	168 (154)	226 (167)	173 (158)	178 (153)	173 (153)
Moisture. %	0·5 (1·15)	0·7 (1·10)	0·5 (0·45)	0·5 (1·05)	0·6 (1·05)	0·7 (0·45)
Green strength. Lb. per sq. in.	2·35 (0·9)	2·35 (0·9)	4·67 (1·6)	1·5 (0·6)	3·4 (1·2)	2·35 (1·9)
Dry strength. Lb. per sq. in. after—						
2 hr. at 200° C.	723 (850)	533 (540)	633 (730)	897 (720)	290 (420)	597 (600)
3 hr. at 200° C.	...	...	...	823	240	817
Hardness of green sample †	95 (98)	98 (96)	70 (85)	98 (97)	96 (95)	98 (87)

* The figures in brackets represent the results of repeat tests, in which mixtures *A, B, D* and *E* had a higher moisture content, however, and were slightly sticky.

† Measured with the Dietert-Ridsdale mould-hardness tester after standing for 4 hr.

consisted of 1500 g. of Chelford sand, 15 g. of G.B. Kordek, 30 g. of petroleum extract and 40 c.c. of water, and was made up by milling dry for 3 min., then wet for 3 min. and finally for 3 min. after the addition of the extract.   All samples tested had a friable surface in the dry state.   Table XVI. represents the results of tests on the mixtures.

TABLE XVI.—*The Properties of Sand Mixes Free from Linseed Oil but Containing G.B. Kordek and Various Petroleum Extracts.*

Extract Groups : Weight of core. G.:	1(2241) 175	1(P.B.3) 175	14(140) 175	1(72) 175	3(105) 170	1(72) + 3(105) (50/50 mixture) 175	P.B.7 175
Permeability No. .	77	81	87	75	88	73	64
Moisture. % .	1·5	1·4	1·6	1·75	1·6	1·9	2·1
Green strength. Lb. per sq. in. . .	3·2	3·3	2·5	4·1	5·2	4·5	3·0
Dry strength. Lb. per sq. in. after—							
3 hr. at 200° C. .	140	127	237	220	257	237	...
5 hr. at 200° C. .	...	...	...	...	...	...	172
6 hr. at 200° C. .	270	230	385	...	...	...	...

Addendum II.

Since the investigation of the six extracts supplied by The Petroleum Board was completed, two further extracts, *viz.,* Group 2(2239) and Group 2(22) have been received and examined.   The viscosity of these two extracts is similar to that of Group 1(72).

Sand mixtures similar to those used in Table III. gave the following dry tensile strengths :

Tensile Strength (lb. per sq. in.) of A.F.A. Test-Pieces ; rammed 3 times ; dried at 200° C. for 2 hr.

Chelford sand. Parts	100	100	100	100	100	100	100
Linseed oil. Parts	2·0	1·6	1·2	1·0	0·8	0·4	0·0
Extract. Parts	0·0	0·4	0·8	1·0	1·2	1·6	2·0
Group 2(2239)	392	413	377	333	303	97	33
Group 2(22)	392	393	375	358	342	147	16

These two extracts are similar in behaviour to Group 3(105) and Group 1(72).

A trial made at a steel foundry in South Wales in which 40% of a commercial core oil was replaced by extract Group 2(2239) gave completely satisfactory results. A trial was also made at a Sheffield steel foundry in which 40% of the linseed oil in a commercial core compound was replaced by extract Group 1(72) with entirely satisfactory results.

Addendum III.[1]

The partial replacement of linseed oil by petroleum extract in the core mixture used at one steel foundry is reported to have resulted in an increase in the number of rejected castings, owing to defects attributed to faulty cores. Cores prepared from the usual core mixture are skin-dried by baking at 140° C. for 1 hr. and then have firm surfaces. Cores prepared in the same way from mixtures in which the linseed oil had been partly replaced by petroleum extract did not develop firm surfaces when baked. These drying conditions are different from those used in the previously reported work on linseed-oil/petroleum-extract mixtures.

This addendum describes tests to ascertain the effect of this lower temperature and shorter time of drying, also of the addition of cobalt naphthanate and of drying at 170° C. The extracts employed were Group 1(2241), Group 1(72) and Group 1A(2419); the latter is described as a re-extracted extract, and was included to see if it had better properties.

Drying Temperature 140° C.—Chelford sand was bonded with linseed oil and extract which had been premixed. The results obtained are shown below :

A.F.A. Tensile Test-Pieces ; rammed 3 times ; dried at 140° C.

Composition of bond.					
Linseed oil. %	2·0	1·6	1·2	1·2	1·2
Group 1(2241). %	...	...	0·8	...	...
Group 1(72). %	...	0·4	...	0·8	...
Group 1A(2419). %	...	...	...	...	0·8
Dry tensile strength. Lb. per sq. in.					
Dried 1 hr.	203	45	17	17	18
Dried 2 hr.	340	335	306	323	249

[1] Received July 27, 1944.

The extract/linseed-oil mixtures all gave low tensile strengths after drying for 1 hr., whereas linseed oil alone gave a fairly good tensile strength. After drying for 2 hr. mixtures containing Group 1(2241) and Group 1(72) had tensile strengths almost as high as that of linseed oil alone, but the strength of the mixture with Group 1A(2419) was lower than that of linseed oil alone. The test-pieces containing extract were soft inside and fairly firm outside after drying for 1 hr.; after drying for 2 hr. they were hard throughout.

The Effect of the Addition of Cobalt Naphthanate was tried on the mixtures containing Group 1(72). The naphthanate was added to the warm extract. The results are shown below; Chelford sand was used as the base sand :

A.F.A. Tensile Test-Pieces ; rammed 3 times ; dried at 140° *C.*

Composition of bond.					
Linseed oil. %	.	.	1·2	1·2	1·2	1·2
Group 1(72). %	.	.	0·8	0·8	0·8	0·8
Cobalt naphthanate. %	.	...	0·004	0·008	0·016
Dry tensile strength. Lb. per sq. in.					
Dried 1 hr.	.	.	17	11	28	26
Dried 2 hr.	.	.	323	253	274	216

The tensile strength after 1 hr. drying was increased slightly by the addition of naphthanate but was lowered after drying for 2 hr.

The naphthanate possibly accelerated the drying of the linseed oil sufficiently to improve the tensile strength after 1 hr. drying, but after 2 hr. drying the oil was tending to be overdried.

Drying at a Temperature of 170° *C.* improved the tensile strength of the mixtures, but the values after 1 hr. drying were still much lower than that for linseed oil alone. The values are given below :

A.F.A. Tensile Test-Pieces ; rammed 3 times ; dried at 170° *C.*

Composition of bond.					
Linseed oil. %	.	.	2·0	1·6	1·2	1·2
Group 1(72). %	.	.	...	0·4	0·8	0·8
Cobalt naphthanate. %.	.	...	...	...	0·008
Dry tensile strength. Lb. per sq. in.					
1 hr. at 140° C.	.	.	203	45	17	28
„ 170° C.	.	.	252	124	54	40
2 hr. at 140° C.	.	.	340	335	323	274
„ 170° C.	.	.	350	400	351	332

Conclusions.—The petroleum-extract/linseed-oil mixtures give A.F.A. cores with firm surfaces only when the drying conditions are sufficient to ensure complete drying of the core. As the drying temperature and time are reduced, the core surface becomes progressively more friable and the interior of the core becomes weaker.

THE CONSTITUTION OF SOME BASIC OPEN-HEARTH SLAGS.*

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SUMMARY.

Fifteen samples of basic open-hearth slags were analysed chemically, and the phases present determined by a combination of methods —the examination of polished and thin sections, the determination of the refractive indices of silicate phases by the immersion method, the use of X-ray powder photographs, and in some cases by the actual separation of the phases present and their chemical analysis. The ratio $CaO/SiO_2(+P_2O_5)$—the B value—ranged from $0 \cdot 9$ to $3 \cdot 3$. The phases identified were olivine, $CaO.RO.SiO_2$ (R is used as a symbol for (Fe, Mn, Mg)); merwinite, $3CaO.MgO.2SiO_2$; dicalcium silicate, $2CaO.SiO_2$; tricalcium silicate, $3CaO.SiO_2$; an oxide phase, RO; dicalcium ferrite, $2CaO.Fe_2O_3$; a magnetite phase, RFe_2O_4; a chromite phase, RCr_2O_4; and free iron. The phase composition was correlated with the chemical composition, and the slags could be classified on the basis of the silicates present and the B values approximately as follows: $B = 0 \cdot 9$–$1 \cdot 4$, olivine slags; $B = 1 \cdot 4$–$1 \cdot 6$, merwinite slags; $B = 1 \cdot 6$–$2 \cdot 4$, dicalcium silicate slags; $B > 2 \cdot 4$, tricalcium silicate slags.

INTRODUCTION.

THE investigations described in this paper were carried out in the latter part of 1942 and the early part of 1943 on behalf of Jernkontoret, of Sweden, and the work was done under the auspices of Metallografiska Institutet in Stockholm. The author's thanks are due to Jernkontoret for permission to publish this paper here. Much of the work was done in collaboration with Mr. Sven Eketorp, at that time assistant in Metallografiska Institutet; he was responsible for taking the samples at the works, for their preparation for analysis and for most of the examination of the polished sections, and credit is due to him for the results obtained. The author is also greatly indebted to Mr. Gosta Phragmén, Director of Metallografiska Institutet, for good advice and helpful discussion on many of the difficulties encountered. All the chemical analyses are the work of Mr. E. Hammarberg, chemist at Metallografiska Institutet.

METHODS USED IN THE INVESTIGATION.

For a critical evaluation of the results obtained a brief review of the methods used and their limitations is necessary.

The methods used can be grouped under five headings :

(1) Examination of thin sections.

(2) Examination of polished sections.

(3) Determination of the refractive indices of transparent phases in the finely powdered slag by the immersion method.

(4) Identification of the phases present by their characteristic lines in an X-ray powder photograph.

(5) Separation of the individual phases from the powdered slag and their chemical analysis.

The examination of a slag in thin sections is most useful for the study of the transparent phases, but information can also be obtained on the crystal form and development of the opaque phases. The primary application of thin sections is for the identification of the silicate or silicates present. The most valuable diagnostic properties are the shape and the size of the grains, the presence or absence of twinning, and the birefringence and optical properties generally. It is not possible, however, to distinguish the different silicates in a thin section by differences in refractive indices, first because the refractive indices of all the silicate phases do not differ greatly one from the other, and secondly because all are much higher than that of the embedding material of the section, canada balsam, the refractive index of which is 1·54. The structure and texture of a slag as seen in thin section also provide valuable information as to its nature. Thus, the study of inclusions in the different phases indicates the sequence of crystallisation : In a crystal containing inclusions, the inclusions have crystallised out of the liquid slag before the enclosing mineral; conversely, crystals free from inclusions have crystallised out early in the solidification process, or may even have been present as solid grains in the liquid slag. In a thin section the relative amounts of the different phases present can be estimated.

The examination of polished sections yields information similar to that obtained from thin sections, and the two methods are largely complementary. Originally polished sections were used for the examination and identification of opaque and semi-opaque phases; the diagnostic features of these phases are power of reflection, hardness, isotropy or anisotropy, and presence or absence of internal reflections (if a phase is not completely opaque, it generally shows internal reflections in the same colour as it does in transmitted light). On account of their low and rather uniform power of reflection in polished sections, silicate phases do not show up prominently, and this method has not been so very much used in their identification. However, in this investigation the work of Mr. Eketorp showed that by etching the polished sections with a solution of 1% of nitric acid in alcohol for 1–10 sec. the silicate phases could be readily differentiated from one another. The individual grains stood out clearly, and differences in shape and size, in etching characteristics,

and in the presence or absence of twinning lamellæ, enabled rapid identification of the silicates also. From a polished section, as from a thin section, the relative proportions of the different phases can be estimated, and, as far as the silicates are concerned, they can be more readily differentiated in an etched polished section than in a thin section.

The determination of the refractive indices of transparent phases in the finely powdered slag is primarily a method for the identification of the silicate phases present. The non-silicate phases, if not completely opaque, have refractive indices higher than those of the commonly available immersion media, and so cannot be identified by this method. The method demands a fairly pure grain of the phase of which the refractive indices are to be determined. A certain minimum size of grain is also necessary for satisfactory results; grains some hundredths of a millimetre in cross-section suffice, but sometimes the slags are so fine-grained that it is difficult or impossible to obtain a grain of sufficient size. Occasionally, too, the silicate grains are so filled with inclusions of other phases that it is not possible to determine their refractive indices. Other limitations are imposed when there is a variation in refractive indices of a single phase because of isomorphous substitutions, and in the rare cases where two different phases have very similar refractive indices. Unfortunately the latter limitation was met with in the present investigation; the refractive indices of merwinite and dicalcium silicate in these slags are so similar that it was not possible to differentiate between them by this method, and this feature was responsible for the overlooking of merwinite for a considerable time. Provided, however, that the above limitations are taken into account, the immersion method is an extremely valuable one for the rapid identification of the silicate phases in a slag.

Examination of X-ray powder photographs is also a method for the identification of the different phases present in a slag. It is superior to the immersion method in that it can be applied to the identification of all the phases present, both transparent and opaque. Nevertheless, even powder photographs have their limitations, and very definite ones. In general, it can be said that the higher the crystal symmetry of a certain phase, the more easily can it be identified in a powder photograph. This is partly due to the fact that, generally, the higher the crystal symmetry, the simpler is the pattern of lines obtained, and partly to the fact that the higher the symmetry the more intense are the lines themselves. Thus, the sensitivity of the method varies greatly for the different phases. In these slags it was found, for example, that metallic iron could be identified even when present in very small amount, and the same was true of the spinels and the RO phase, whereas dicalcium silicate and merwinite gave poor powder photographs with weak and diffuse lines even when present in large amount. When a slag

contains two or more phases giving complicated patterns of lines of low intensity, then the interpretation of the powder photograph and the identification of the different phases may be difficult, if not impossible, on account of superposition and coincidence of lines of different phases.

The above methods of investigation were applied to all the slag samples. Another method was tried on some slags, and that was the actual separation of the different phases one from the other and their individual analysis and examination. The slags were finely powdered, and separated into fractions of different densities by centrifuging in Clerici solution * of certain concentrations. Thus it was found that the fraction with density $<3\cdot4$ consisted generally of rather pure silicate, and the fraction with density $>4\cdot2$ of the RO phase, always admixed with metallic iron and often with other opaque phases also. The iron and any magnetite present in the latter fraction could then be separated by a hand magnet. A few trials were also made on the use of an electromagnet for separations from the powdered slag, and it was found with some slags that repeated separation left a residue of nearly pure silicate, all the other phases being attracted by the electromagnet. This work was largely exploratory, and was not carried very far ; but it became evident that for a fundamental investigation of slag systems the separation of the individual phases from the slags, their analysis and the correlation of the chemical composition with their optical and other physical properties are essential. There are many difficulties in the separation of pure phases from the slags, principally on account of their fine-grained nature, but these difficulties can be countered by improvements in technique. A promising method of separation, which was not tried in the present investigation, is the selective solution of the different phases in suitable reagents. A recent paper by Kristoffersen [1] gave a detailed account of the application of this method to the separation of the phases from basic slags and reveals its possibilities.

CHEMICAL COMPOSITION.

Table I. gives the chemical compositions of the different slags examined. These slags came from two different works, those without P_2O_5 (Nos. 3, 4, 8, 10 and 11) from the one, the remainder from the other. Slags 3 and 10 were taken at different times during the same charge, likewise Nos. 8 and 11, Nos. 1, 6, 13 and 14 and Nos. 2, 7, 9 and 12.

There is one source of error in these analyses, and that lies in the determination of the iron oxides. All these slags contain metallic iron, generally as small pellet-like inclusions ; the amount of this free iron is very variable, apparently depending largely on the viscosity of the liquid slag—the more viscous the slag the greater

* An aqueous solution of equal parts of thallous formate and thallous malonate ; maximum density at room temperature approximately 4·3.

TABLE I.—*Analyses of Slags from the Basic Open-Hearth Process.*

Sample No.	SiO_2. %.	CaO. %.	MgO. %.	MnO. %.	FeO. %.	Fe_2O_3. %.	Al_2O_3. %.	Cr_2O_3. %.	P_2O_5. %.	B Value. $\dfrac{CaO}{SiO_2(+P_2O_5)}$.
1	32·76	30·93	10·34	8·37	13·1 *	...	1·70	...	1·78	0·90
2	33·90	33·04	7·85	9·11	11·5 *	...	2·23	...	1·17	0·94
3	33·01	37·60	13·15	7·40	5·19	0·94	2·21	...	...	1·14
4	32·40	37·70	11·64	7·28	6·61	0·83	2·56	...	...	1·16
5	27·71	34·84	10·61	9·04	12·1 *	...	2·56	0·83	2·38	1·16
6	26·04	38·16	10·70	6·08	11·4 *	...	2·42	...	4·99	1·23
7	23·45	37·56	8·24	5·86	13·6 *	...	2·17	4·15	5·02	1·32
8	30·74	43·70	9·18	6·20	6·44	1·27	2·06	...	...	1·42
9	22·42	40·67	8·34	5·10	12·6 *	...	2·23	3·81	4·44	1·52
10	25·60	39·30	17·01	5·15	8·49	1·50	2·75	...	...	1·54
11	27·29	46·40	9·38	4·38	8·77	1·37	2·05	...	...	1·70
12	17·65	43·08	7·17	4·11	15·6	3·3	2·07	3·22	4·01	1·99
13	16·44	49·80	8·77	3·39	12·0	3·1	1·32	...	4·53	2·37
14	14·88	53·92	7·93	3·11	10·5	2·7	1·29	...	4·74	2·75
15	13·15	50·41	6·13	4·07	16·1	5·4	1·67	0·69	2·47	3·23

* Total iron content calculated as FeO.

being the amount of metallic iron trapped in it. Although the powdered slag was always run over a magnet before analysis, this treatment did not suffice to remove all the free iron, some being always present in the analysed samples. The presence of this free iron affects the amounts of FeO and Fe_2O_3 found when both are determined, and results in too low a value for Fe_2O_3 and too high a value for FeO. The magnitude of this error is unknown, but is probably small, as the amount of free iron found in the analysed samples was never very great.

The significance of the chemical composition in regard to the nature of the slags will be fully discussed in a later section of this paper, and only the most fundamental features will be touched upon here. It can be seen that the compositions of the slags are essentially determined by the amounts of SiO_2, CaO, MgO, MnO and the oxides of iron present, these components making up about 90% of the slags. A small amount (1–3%) of Al_2O_3 is always present. In the slags from the one works P_2O_5 is always present, in amounts up to 5%. A noteworthy feature of these slags is the presence of appreciable amounts of Cr_2O_3 in some of them. The main components of all the slags are SiO_2 and CaO, the sum of which always lies between 60% and 75%. It is obvious that there is a fundamental connection between CaO and SiO_2 in these slags, the percentage of CaO increasing as that of SiO_2 decreases. This is, of course, a reflection of the smelting process, which consists in the continual addition of lime to the furnace as the refining proceeds.

On the whole, the relation between the CaO and SiO_2 controls the constitution of the slag, and for this reason the analyses in Table I. are arranged according to the ratio CaO/SiO_2, which is here denoted by B. Since the phosphorus present in these slags does not form a separate phase, but substitutes silicon, allowance is made for it in calculating B, in order that the phosphorus-containing

slags may be more readily compared with the phosphorus-free slags. This allowance has been made by simply adding the percentage of P_2O_5 present to that of SiO_2 when calculating B, a rough and ready procedure, but adequate for the purpose, as will be seen later.

In addition to the components determined in the analyses a little fluorine is also present in slags 13 and 14. The source of this fluorine lies in the addition of fluorite, CaF_2, 25 kg. of which was added to the bath just before these slags were drawn off. The percentages of fluorine in slags 13 and 14 were not specially determined, but, since the total amount of slag in the furnace was about 1200–1500 kg., this addition of CaF_2 (fluorine, 49%) would correspond to approximately 1% of fluorine in these slags, provided that none of it was lost in any way.

Phase Composition.

The phase compositions of these slags are given in Table II. Uncertain identifications are indicated by a query. The lattice dimensions of the RO phase in the different slags are also included in the Table. A description of the individual phases follows.

Olivine, $CaO.RO.SiO_2$.—(R is used throughout this paper as a group symbol for (Fe, Mn, Mg).) This phase has often been identified in basic slags, and is generally referred to as monticellite. Strictly, however, monticellite is the mineral $CaO.MgO.SiO_2$, and this slag phase differs from monticellite in having a great part of the magnesium replaced by iron and manganese. The properties of this slag phase are therefore rather different from those of the natural mineral; as this phase has the olivine structure it is referred to in this paper simply as olivine. Its composition differs somewhat from slag to slag, the proportions of iron, manganese and magnesium varying, and the ratio $CaO : RO$ probably also deviates from the ideal $1 : 1$. Its optical properties thus vary somewhat; the refractive indices are approximately $\alpha = 1 \cdot 66$, $\beta = 1 \cdot 68$, $\gamma = 1 \cdot 69$, and the birefringence is about $0 \cdot 03$. Olivine is generally easy to recognise in slags by its optical properties, having lower refractive indices and a higher birefringence than any other of the silicates that occur. It often shows a typical crystal development in thin and polished sections, the crystals appearing as long laths. (Merwinite has a very similar crystal development, and is difficult to distinguish from olivine in thin sections except when the merwinite shows its characteristic twinning.) Olivine gives a characteristic powder photograph, by which it can be identified even when intimately intermixed with other phases.

A rather comprehensive discussion of slag olivines is given in a paper by Beliankin and Ivanov.[2]

Merwinite, $3CaO.MgO.2SiO_2$.—The composition of this phase does not appear to vary very much from the ideal formula, judging from the constancy of optical properties recorded for merwinite of different origins. The merwinite from these basic slags had $\alpha =$

TABLE II.—*Phase Compositions of Slags.*

Ol = olivine; Me = merwinite; C_2S = dicalcium silicate; C_3S = tricalcium silicate; RO = oxide phase.
× indicates presence; parentheses imply small amounts only. × ? indicates doubtful identification and
(?) doubtful identification in small amounts only.

Slag No.:	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.
B value	0·90	0·94	1·14	1·16	1·16	1·23	1·32	1·45	1·52	1·54	1·70	1·99	2·37	2·75	3·23
Ol	×	×	×	×	×	×	×	—	—	—	—	—	—	—	—
Me	—	—	(×)	(×)	—	—	(×)	×	× ?	×	(?)	—	—	—	—
C_2S	—	—	—	—	—	—	—	—	(×)	(?)	×	×	×	(?)	—
C_3S	—	—	—	—	—	—	—	—	—	—	—	—	×	×	×
RO	(?)	(?)	(×)	(?)	×	×	×	(×)	×	×	×	×	×	×	×
a in A.			4·28		4·28	4·30	4·29		4·31	4·24	4·30	4·28	4·30	4·26	4·28
RFe_2O_4	—	—	(×)	(×)	—	—	—	(?)	—	—	—	—	—	—	—
RCr_2O_4	—	—	—	—	—	—	(×)	—	(×)	—	—	(×)	—	—	—
$2CaO.Fe_2O_3$	—	—	—	—	—	—	—	—	—	—	—	(?)	× ?	× ?	× ?

1·711, $\gamma = 1·729$ ($\pm 0·003$), perhaps somewhat higher than the figures given by Phemister.[3] This may be due to a small amount of substitution. The silicate in slags 8 and 10 consisted practically entirely of merwinite, and by centrifuging in Clerici solution a merwinite concentrate was obtained from slag 10 which was contaminated with about 5–10% of the RO phase and probably with a little dicalcium silicate also. This concentrate was analysed, with the following result :

SiO_2.	Al_2O_3.	FeO.	MnO.	CaO.	MgO.
31·49%	2·07%	4·13%	3·30%	46·18%	11·80%

On account of contamination with other phases it is not possible to determine the exact composition of the merwinite from the above analysis. The analysis indicates, however, that it corresponds closely to the ideal formula, probably with a little substitution of manganese and iron for calcium and magnesium.

For a long time the presence of merwinite in these slags was overlooked or the phase confused with olivine or dicalcium silicate. In thin sections it appears as elongated crystals very similar in every way to olivine, except when it shows the characteristic polysynthetic twinning. The refractive indices are very close to those of the dicalcium silicate from these slags, and thus do not serve to differentiate it from this phase. Merwinite gives a complex and rather weak powder photograph, and its identification when mixed with dicalcium silicate is apt to be uncertain. Merwinite is most easily recognised in these slags by its refractive indices in conjunction with the shape of the crystals. Dicalcium silicate, which has similar refractive indices, appears always as rounded grains and never as the laths which are typical of merwinite. The distinctive form of the crystals of these substances is most readily seen in etched polished sections.

Dicalcium Silicate, $2CaO.SiO_2$.—This phase, hereafter referred to as C_2S, is said to occur in three forms, α, β and γ. The α-form is stable at temperatures from 1420° C. to its melting point at 2130° C., the β-form is stable between 675° and 1420° C., and the γ-form is stable below 675° C. In pure C_2S preparations it is extremely difficult to obtain the α and β forms, on account of their very strong tendency to invert to the γ-form on cooling. However, the C_2S in these slags does not undergo this inversion, presumably on account of the presence of foreign elements in solid solution.

The author has not been able to decide which of the two high-temperature forms of C_2S, α or β, occurs in these slags. The differences in optical properties, such as refractive indices, are very slight, and are overshadowed by variations caused by isomorphic substitutions. It is not possible to distinguish the two forms with certainty by powder photographs, because, as Brandenberger[4] has shown, powder photographs of the two forms are very similar. In addition, both forms give powder photographs of low intensity,

probably on account of a low order of symmetry. If distinct, α-C_2S and β-C_2S are very similar compounds, and it is not really necessary for the present investigation to attempt to distinguish between them. Therefore, the dicalcium silicate present in these slags will be referred to simply as C_2S, without thereby expressing any opinion as to whether it is the α- or the β-form.

The refractive indices of C_2S vary noticeably from slag to slag, on account of substitution. Thus, α varies from 1·703 to 1·715, and γ from 1·713 to 1·729; this variation seems mainly due to substitution of silicon by phosphorus, which lowers the refractive indices. The most useful diagnostic feature of C_2S is the characteristic rounded shape of the grains as seen in thin sections and polished sections, and the fluted surface of the grains in the etched polished sections.

A rather pure concentrate of C_2S was extracted from slag 11 by centrifuging in Clerici solution. This concentrate, which was contaminated with about 5% or less of the RO phase, was analysed with the following result :

SiO_2.	Al_2O_3.	FeO.	MnO.	CaO.	MgO.
33·10%	1·79%	4·06%	3·16%	51·82%	5·27%

This analysis confirms the identification of this phase as C_2S, and shows that there is a little replacement of calcium by magnesium, iron and manganese. The refractive indices of this particular sample were $\alpha = 1·712$, $\gamma = 1·727$ ($\pm 0·003$).

Tricalcium Silicate, $3CaO.SiO_2$.—This phase is often symbolised by C_3S. It has been known for a number of years as a phase in basic slags, and the properties of C_3S from such slags have been described by Andersen and Lee [5] and by Guttmann and Gille.[6] Its refractive indices are $\omega = 1·722$, $\varepsilon = 1·716$, and overlap those of C_2S, but its birefringence is considerably lower, and there is little chance of confusion.

C_3S is rather easy to identify in slags. In thin sections it shows characteristic crystal outlines, occurring either as long needle-like crystals or as rather short, broad laths. These crystals are not likely to be confused with olivine or merwinite, as their birefringence is very much less. Occasional basal sections are also found; they often have indistinct hexagonal outlines, and in convergent light show an indistinct uniaxial cross. C_3S may also be identified in powder photographs, but its pattern resembles to some extent that of C_2S, the strongest lines in both practically coinciding. Neither the structure of C_3S nor that of C_2S has yet been determined, so that it is not known whether this resemblance in powder photographs indicates a resemblance in structure. However, from the structural similarity between norbergite, $MgF_2.Mg_2SiO_4$, and forsterite, Mg_2SiO_4, it is tempting to suggest a similar structural relation between $C_3S(CaO.Ca_2SiO_4)$ and $C_2S(Ca_2SiO_4)$.

The Oxide Phase, RO.—This phase, which is present in all the

slags examined, except perhaps some of those with low B values, consists of a solid solution of the monoxides of iron, manganese and magnesium, with also a little calcium (perhaps about 5% or less) in those slags especially rich in CaO. Some Fe_2O_3 is probably also present in solid solution. Usually this phase is black and opaque, but when very rich in magnesium it becomes yellow-brown and translucent. Its crystal system is cubic. It is easily identified in powder photographs, as it gives a photograph with few but intense lines. By measuring the powder photographs the lattice dimensions of this phase can be determined, and by comparison with the lattice dimensions of the components some indication of the composition can be obtained.

Study of the binary systems of the different oxides which enter into this oxide phase has shown that in the quaternary system FeO–MnO–MgO–CaO there must be an extensive two-phase region. It might, therefore, be expected that in these slags two different phases of the RO type could occur in one and the same slag. However, in no slag was more than one RO phase found. Evidently in these slags there was complete miscibility of the various oxides at the temperature of crystallisation. Perhaps at ordinary temperatures the composition of the RO phases in these slags falls within a two-phase region, but, if so, the rate of cooling had been so great that the unmixing that is theoretically to be expected did not take place.

Dicalcium Ferrite, $2CaO.Fe_2O_3$.—This substance crystallises in the orthorhombic system and has high refractive indices. In thin sections it has a yellowish-brown colour, and shows birefringence under crossed nicols. Several investigators have identified it as a phase in basic slags. It appears to be present in slags 13, 14 and 15, but positive proof of this identification is lacking. It was identified in these slags as a fine-grained yellow-brown birefringent phase answering to the description of dicalcium ferrite. However, it was not possible to isolate it from these slags for analysis, and it could not be identified in the powder photographs for lack of a comparison photograph of pure dicalcium ferrite. Hence, the identification is queried in Table II.

Other Phases.—A few other phases also occur in very small amount. As previously mentioned, metallic iron occurs in all the slags, generally as small rounded pellets. A spinel of the magnetite type, RFe_2O_4, was identified in powder photographs of the magnetic concentrate from some of the slags with low B values. A chromite phase, RCr_2O_4, occurs in slags 7, 9 and 12, the analyses of which show an appreciable amount of Cr_2O_3; this phase was identified as reddish-brown translucent isotropic grains in thin and polished sections, and the identification was confirmed by the characteristic lines appearing in powder photographs of these slags. Free lime is never present in any amount, even in the slags with high B values, and occurs only as partly assimilated remnants of the lime added during the refining process.

CORRELATION BETWEEN PHASE COMPOSITION AND CHEMICAL COMPOSITION.

Since the silicate phase or phases always make up over 50% of the bulk of the slag, a simple classification can be based on the dominant silicate in the slag. Thus, from Table II., slags 1 to 7 can be called olivine slags, slags 8, 9 and 10 merwinite slags, slags 11, 12 and 13 C_2S slags and slags 14 and 15 C_3S slags. Of course, occasionally it happens that two of the silicate phases are present in approximately equal amounts, in which case it is more or less arbitrary under which of them it is classified. This is the case with slag 13, for example.

The above classification indicates a first correlation between phase composition and chemical composition. In Table II. the slags are arranged in order of increasing B values, and it can be seen that there is a distinct connection between the silicate(s) present and the B values, thus :

$B =$ 0·9–1·4, olivine slags.
      1·4–1·6, merwinite slags.
      1·6–2·4, dicalcium silicate slags.
      above 2·4, tricalcium silicate slags.

This division is not entirely satisfactory, nor can it be expected to be, because the calculation of B takes no account of the amounts of the oxides of magnesium, manganese and iron present. These oxides are essential constituents of the olivine phase and enter into solid solution in C_2S and C_3S in small amounts, and thus alter the phase relations between these various silicates. The amount of MgO in the slag is especially significant in determining the presence or absence of merwinite, as magnesium is an essential constituent of this silicate and apparently can be only slightly replaced by other elements. Thus, although the B value gives a useful indication as to the silicate(s) to be expected in a certain slag, consideration must also be given to the amounts of components other than CaO and SiO_2, especially MgO.

At the beginning of the refining process in the basic open-hearth process the slag consists practically entirely of olivine, $CaO.RO.SiO_2$. The continual addition of CaO leads eventually to the formation of dicalcium and tricalcium silicate, and all the RO originally combined in the olivine is set free as the oxide phase. The amount of oxide phase present generally reaches a maximum in the dicalcium silicate slags and then begins to decrease, partly owing to the increase in the amount of silicate phase with the formation of tricalcium silicate, and probably in part because of the abstraction of iron from it with the formation of dicalcium ferrite, which seems to form only at B values greater than 2.

The above discussion suffices to indicate the distribution of the essential components among the phases present in the solid slag. Some observations will now be made on the part played by minor and non-essential components and their distribution among the

slag phases. Thus, Al_2O_3 is present in all slags in more or less constant amount, about 2%. This Al_2O_3 does not form any independent phase, but occurs in solid solution in other phases. Some is present in the silicates, but a good deal appears to concentrate in the non-silicate phases, *i.e.*, in the RO phase and probably especially in the dicalcium ferrite, when this phase is present. The presence of a trivalent element such as aluminium in the RO phase must cause an adjustment of the structure in order to accommodate it, and this adjustment evidently consists in the development of empty metal positions in the lattice, just as the invariable presence of trivalent iron in pure wüstite (ferrous oxide) is compensated for by empty lattice positions.

The P_2O_5, which is present in some of the slags in amounts of up to 5%, does not appear to build any independent phase either, but goes entirely into the silicate phases, PO_4''' groups replacing SiO_4'''' groups. This substitution leads to a decrease in the total number of negative valencies, which must be compensated for in some way, either by the development of empty lattice points or by adjustments in the number and/or valencies of the metal ions. Such substitutions of PO_4''' for SiO_4'''' and *vice versa* are by no means uncommon and are being increasingly recognised. It was thought that the P_2O_5 in some of these slags might form an apatite phase, especially in slags 13 and 14, which presumably contain fluorine, but careful search did not reveal any such phase. It was noticed that the dicalcium silicate in the phosphatic slags had decidedly lower refractive indices than the dicalcium silicate in the non-phosphatic slags, and this feature evidently reflects the presence of phosphorus in the dicalcium silicate of the phosphatic slags.

The appreciable percentage of Cr_2O_3 in slags 7, 9 and 12 does not enter into the usual phases to any extent, but forms a chromite phase, RCr_2O_4.

The Fe_2O_3 does not enter into the silicate phases to any appreciable extent. When dicalcium ferrite is present it goes into this phase; otherwise it is in solid solution in the RO phase, as explained in discussing Al_2O_3, and in slags 3 and 4 it is apparently present largely as a phase of the magnetite type, RFe_2O_4.

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A STUDY OF THE SURFACE FILM ON CHROMIUM-NICKEL (18/8) STAINLESS STEEL.*

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SYNOPSIS.

The surface film was stripped from chromium-nickel (18/8) austenitic stainless steel and metals present were determined by chemical analysis; the contents of the corresponding oxides were computed. The thickness of the film as measured by total oxides present (Cr_2O_3, Fe_2O_3, NiO) increases with the degree of polish. There is a marked enrichment of chromium in the film as compared with the underlying steel, and this enrichment also increases with the degree of polish. Films from brightly-polished specimens contain about 90% of chromic oxide, the balance being mostly ferric oxide. No enrichment of nickel has been observed. The use of chromic oxide as a final polishing material does not appreciably affect the content of chromic oxide in the film. When alumina is used for the final polishing this substance is introduced into the film and the concentration of chromic oxide is simultaneously reduced. Electrode potential measurements on specimens immersed in $N/200$ sodium chloride solution have confirmed that polishing with alumina yields a less passive surface than polishing with chromic oxide; also that a surface from which the film has been removed is considerably less passive than the polished surface. It is suggested that enrichment of chromium (as chromic oxide) in the film is associated with surface flow, the rate of oxidation being controlled partly by the free energies of formation of the respective oxides, and probably to a greater extent by selective oxidation arising from the restriction of oxygen at the interface between the metal and polishing material.

FOLLOWING the previous work of the authors on the air-formed film on iron and mild steel,[1] it had been intended to explore the possibilities of a similar technique applied to surface films on " stainless " alloy steels. The experiments now to be described, using austenitic (18/8) chromium-nickel steel, represent a preliminary programme of work, much of which had been completed before the war, but which was subsequently suspended on account of pressure of more urgent problems. Recent developments in this field suggest the desirability of placing the results on record, particularly in view of their possible practical implications.

The earliest work on the removal of surface films from ferrous materials was carried out by U. R. Evans,[2, 3] who succeeded in stripping films from passive and heat-treated iron by the use of a solution of iodine in aqueous potassium iodide. It was discovered that iodine has the property of attacking metallic iron preferentially along the boundary between metal and oxide, thus permitting (since it has no action on the oxide itself) the separation of the film from the metal. In the present work it was further found that for this separation to yield a film representing *quantitatively* the oxide present on the metal, it is necessary to exclude both water and oxygen from the system. This led to the technique already described,[1] in which a solution of iodine in anhydrous methyl alcohol is used as the stripping reagent in an apparatus designed to facilitate the removal of atmospheric oxygen.

Reference should also be made to the anodic method of film stripping developed by U. R. Evans and J. Stockdale.[4]   By long anodic treatment of 13% chromium steel these workers obtained, in addition to opaque flakes, a very thin transparent film carrying striae representing the original abrasive treatment.   Their attempts to obtain the film from austenitic 18/8 chromium-nickel steel yielded a skin containing so much residual metal as to be opaque.   The modified (chemical) technique now employed has been found to be applicable to this type of steel, and the film so obtained is believed to be free from contamination.   The present paper refers to results obtained from the examination of this film.

Experimental.

The 18/8 chromium-nickel steel used in the experiments was supplied, through the kind offices of the late Dr. W. H. Hatfield, F.R.S., in the form of sheet, 0·45 mm. thick.   The following surface treatments have been examined :

Series I :

(a) Abraded with Hubert No. 1 emery paper in the laboratory.

(b) Ground and polished industrially, low-grade polish.

(c) As (b), except that the works method followed was such as to give a rather better polish.

(d) Ground and polished industrially, high-grade polish (mirror finish).

Note.—It was known definitely that no chromium oxide was used in the polishing by processes (b) and (c).   It is possible that chromic oxide was used in the later stages of (d), but unfortunately the point was overlooked until it was too late to be checked with certainty. In order to put the effect of polishing treatment beyond doubt, it was decided to carry out a further series of tests on sheet material polished specially for the work (arrangements for which were kindly made by Dr. Hatfield) as follows :

Series II :

(a) High-grade polish (mirror finish), using alumina as the final polishing material.

(b) High-grade polish (mirror finish), using chromic oxide as the final polishing material.

Note.—The degree of polish in (a) and (b) was, as nearly as could be arranged, identical.

Specimens measuring $5 \times 2·5$ cm. were cut from the polished sheets and kept in a desiccator.   Immediately before use in a stripping experiment, each specimen was degreased by passage through several baths of pure benzene, and finally " trimmed " with shears to ensure freshly-cut edges (this was necessary for the success of the stripping), the precise dimensions of the specimen being determined after the experiment.

The general procedure followed closely that adopted in the previous work, and the same apparatus was employed ; this is shown diagrammatically in Fig. 1.   Anhydrous methyl alcohol is refluxed with and distilled from quicklime, and redistilled from calcium metal.   " AnalaR " iodine is dried over silica gel in a desiccator for several days, 7 g.* are dis-

* 3·5 g. were used for alumina-polished specimens, from which the film was more easily detached.

solved in 60 ml. of the dry alcohol, and the solution is filtered through a Whatman No. 50 filter-paper into flask A (Fig. 1). Flask B contains about 150 ml. of the dry alcohol. After a preliminary passage of nitrogen, the specimen S is hung on the glass hook carried in the rubber stopper of the reaction-tube R, which is then thoroughly swept out with dry oxygen-free nitrogen (commercially " oxygen-free "—passed over heated copper and phosphoric oxide). This is effected by opening the taps T and V (clips a and b being open, c and d closed, and tap W open to the exit D). Air is removed from flask A by closing b and opening d, e and g (U being open to D), the iodine solution being boiled and cooled three times while nitrogen is passing through. A similar procedure is employed to de-aerate the alcohol in B, f and h being open. The iodine solution is then forced into the tube R (T opened to U; g, e, d, b open, W open to exit D) so that the specimen S is completely immersed. W and b being closed, the specimen is left sufficiently long (normally 1 hr. for abraded, 5 hr. for polished specimens) to ensure the " undermining " of the film.

Fig. 1.—The Apparatus (reproduced by permission from the *Journal of the Chemical Society*, 1939, p. 624).

The specimen, with the film still clinging, is washed with anhydrous methyl alcohol while in the nitrogen-filled reaction tube; it is then transferred to a dish of the dry alcohol where the film floats off, breaking up at the same time into small difficultly-visible fragments. The film removed from 18/8 steel is almost colourless, or very pale brown by transmitted light; by reflected light it has a milky appearance. Under the microscope it appears clean, except for occasional small particles, presumably of ferric oxide. Films removed from abraded specimens show the original scratch lines.

For the purpose of analysis the film fragments are filtered on to a Whatman No. 44 filter paper, the films from three separate stripping operations (in order to compensate for the small quantity of material) being collected on one filter.* The fragments are washed with dry methyl alcohol, dried, and burnt in a platinum crucible. The residue is fused with a mixture of 0.2 g. of sodium carbonate and 0.1 g. of potassium chlorate, the fusion extracted with 2 ml. of concentrated H_2SO_4, and the solution made up to 100 ml. A blank fusion is also carried out, and the resulting 100-ml. solution used for standards in subsequent analyses. Estimations of iron, chromium, nickel and aluminium (the last-named only in cases where the material has been polished with alumina) are made as follows :

Iron.—10 ml. of test solution are pipetted into a Nessler tube and 5 ml. of N ammonium thiocyanate added. The colour is compared with that of a standard prepared from the blank fusion and a standard iron solution.

Standard iron solution : 1 ml. ≡ 0.01 mg. of iron.

* In the previous work the films from individual stripping experiments were examined separately.
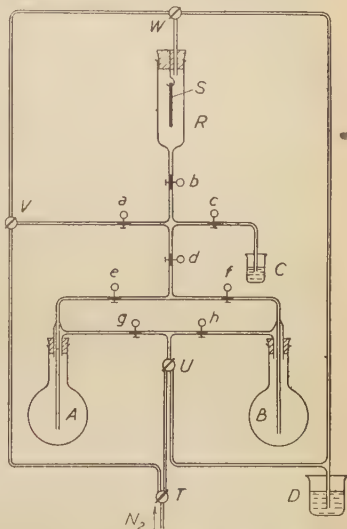
Chromium.—10 ml. of test solution are pipetted into a 100-ml. beaker, 10 ml. of silver nitrate (10%) solution and 2 g. of ammonium persulphate added, and the whole diluted to 25 ml. The solution is boiled vigorously for 20 min. (the volume being maintained at about 25 ml.) and then cooled rapidly to room temperature. The test is carried out by adding 10 drops of a 0·2% alcoholic solution of diphenyl-carbazide and 10 ml. of 10% sulphuric acid, mixing, and comparing

TABLE I.—*Data from Chemical Analyses of Films.*

Reference Number.	Surface Finish.	Contents of Film.* μg. per sq. cm.			Approximate Total Oxides in Film. μg. per sq. cm.	Calculated Approximate Film-Thickness.† Å.		Cr/Fe Ratio in Film.
		Fe_2O_3.	Cr_2O_3.	Al_2O_3.		(1).	(2).	
A. Influence of Degree of Polish.								
22 23	} Abraded, I*a*. {	2·0 2·1	1·4 1·5	... } ... }	3·5	70	30 {	0·7 0·7
20 21	} Low-grade polish, { I*b*.	0·8 0·8	2·9 3·1	... } ... }	3·7–3·9	75	45 {	3·5 3·8
15 16	} Low-grade polish, { I*c*.	0·85 0·8	3·4 3·1	... } ... }	4·0–4·2	80	45 {	4·0 3·8
17 19	} High-grade polish, { I*d*.	0·5 0·45	3·7 4·2	... } ... }	4·2–4·6	85	50 {	7·2 9·3
B. Influence of Polishing Material (High-grade Polish, II).								
26 27 30 31	} Alumina polish. {	1·6 1·6 1·2 1·4	4·1 4·2 3·5 3·3	N.d.‡ N.d.‡ 2·1 2·6	7·0–8·0	160	95 {	2·5 2·6 2·8 2·3
28 29 32	} Chromic oxide { polish.	0·8 0·6 0·6	6·8 5·7 5·4	... ...	6·0–7·5	130	75 {	8·5 9·3 8·7
C. Influence of Heat Treatment.								
12 13 14	} Low-grade polish, { I*c*. Heated at 500° C. for 17 hr.	7·4 8·4 7·2	16·0 16·0 14·8	... ...	22·0–25·0	450	265 {	2·1 1·9 2·0

* Determined as metal, calculated as oxide.
† Values expressed to nearest 5 Å., (1) on "apparent" area of specimen, (2) on estimated "real" area.
‡ Not determined.

the colour against that of a standard chromium solution to which the same additions have been made.

Standard chromium solution : 1 ml. ≡ 0·01 mg. of chromium (0·0283 g. of $K_2Cr_2O_7$ in 1000 ml.).

Nickel.—10 ml. of test solution, made slightly ammoniacal, are diluted to about 40 ml.; 2 ml. of an almost saturated alcoholic solution of dimethylglyoxime are added, then 1 ml. of sodium hypochlorite (or 1 ml. of 10% calcium hypochlorite, freshly made and filtered). The test is diluted to 50 ml. and compared with standards similarly prepared.

Standard nickel solution : 1 ml. ≡ 0·01 mg. of nickel.

Aluminium.—10 ml. of test solution are treated with 10 ml. of N NaOH and diluted with water to a known volume (*e.g.*, 50 ml.); 1 ml. of saturated ammonium carbonate solution with 1 ml. of haematoxylin is then added, and after 15 min. 1 ml. of 30% acetic acid. The colour is compared with standards prepared from potash alum.

Standard aluminium solution : 1 ml. $\equiv$ 0·01 mg. of aluminium.

Results and Discussion.

Composition of Films and Surface Condition.

Experimental and calculated data with respect to the composition of the films are given in Tables I. and II. Iron, chromium and aluminium,

TABLE II.—*Approximate Percentage Composition of Films.*

Reference Number.	Surface Finish.	Concentration of Oxide in Film. By Weight. %.*		
		Fe_2O_3.	Cr_2O_3.	Al_2O_3.
A. Influence of Degree of Polish.				
22 23	} Abraded, I*a*.	59 58	41 42	... ...
20 21	} Low-grade polish, I*b*.	22 21	78 79	... ...
15 16	} Low-grade polish, I*c*.	20 20	80 80	... ...
17 19	} High-grade polish, I*d*.	12 10	88 90	... ...
B. Influence of Polishing Material (High-Grade Polish, II.).				
30 31	} Alumina polish.	18 19	51 45	31 36
28 29 32	} Chromic oxide polish.	10 10 10	90 90 90	... ...
C. Influence of Heat Treatment.				
12 13 14	} Low-grade polish, I*c*. Heated at 500° C. for 17 hr.	32 34 33	68 66 67	... ...

* Values are calculated directly from the data of Table I. and expressed to the nearest unit figure without any implication as to the degree of accuracy involved.

estimated as metal, are expressed as Fe_2O_3, Cr_2O_3 and Al_2O_3, respectively. The last-named, when present, is obviously derived as such from the polishing material. The assumption that iron and chromium are present in the surface film as the respective oxides may be regarded as a reasonable extrapolation from the knowledge of the air-formed film on iron; it is also consistent with available electron-diffraction evidence relating to stainless-steel surfaces.* Although the possibility cannot be excluded

* T. Tokumitu [5] concluded from the electron-diffraction examination of stainless-steel surfaces after heating at different temperatures that the naturally occurring film of oxide is the $(Fe, Cr)_2O_3$ form. This confirmed the findings of S. Miyake [6] (using a similar technique) with respect to the presence of $Fe_2O_3.Cr_2O_3$ solid solution.

that some unoxidised metal (both iron and chromium) is present,* it is reasonable to conclude that the film is made up essentially of the mixed oxides.   In Table I. these are reported as µg. per sq. cm. of surface area and in Table II. as percentages by weight of the total oxide content of the film.

The presence of nickel was detected in all the samples examined, but only in two (Nos. 30 and 31, alumina-polished specimens, Series II.), and then without any margin, was the content sufficiently high to fall within the limits of satisfactory measurement.   (As the minimum amount of nickel that can be estimated in a given determination is about 10 µg., this corresponds, taking into account the area of the films employed, to about 0·13 µg. of nickel or 0·17 µg. of NiO per sq. cm.† ; alternatively, it represents rather less than 2% of the total oxide content of the film.)   For this reason nickel is not included in the Tables but is discussed in the text (infra); its omission from Table II. cannot sensibly affect the approximate percentage values of the major constituents.

It is apparent (see Table I., A) that the Fe_2O_3 content of the film decreases as the degree of polish increases, e.g., it is 4 times as great in the film from the abraded as from the most brightly polished specimens. (The higher Fe_2O_3 content of films from specimens polished with alumina is discussed later.)   On the other hand, there is a marked increase of Cr_2O_3 with increase of polish, irrespective of whether chromic oxide is used in the polishing process.   The effect of polishing is brought out most strikingly by considering the ratio of chromium to iron ; 0·24 in the underlying steel, this increases to 0·7 in the film from abraded specimens and to 3·8 with even a moderate (" low-grade ") polish.   Although there is some doubt whether or not chromic oxide was used in the final stages of the high-grade polish (Nos. 17 and 19), it is believed that the very great increase in the Cr/Fe ratio to a mean value of 8·3 (the individual value of 9·3 is nearly 40 times greater than the ratio in the basis steel) is entirely consistent with the effect of polish per se.   This is borne out by the comparatively small increase in the chromium content (cf. results from the low-grade polish for which chromic oxide was definitely not used) and the continued marked fall in iron content, which is clearly a characteristic of increasing intensity of polish.

The matter is rendered clearer in Table II., where it is seen that the concentration of chromic oxide in the films, even from the low-grade polish, is as high as 80% of the total oxide, a value that is realised very closely in each of the four separate determinations.   Considering the much more advanced polish represented by the high-grade polish, an increase of the chromic oxide content to 90% is no more than would be expected on the basis of polish alone, and no evidence is afforded of any appreciable contribution of chromic oxide from the polishing material.   The results (Table I.) support the conclusion that a relationship subsists between the efficiency of the polishing and the ratio of chromium to iron in the film.

The low content of nickel in the films is in marked contrast with the enrichment of chromium.   To confirm that the technique itself was not responsible for failure to detect any such enrichment of nickel that might, in fact, have occurred, supplementary experiments were carried out on specimens of sheet nickel on which oxide films had been produced by heat treatment, the amount of nickel in the film being calculated from the

* In the earlier work (1) it was concluded that a little metallic iron must be present in the thin oxide films produced by heating iron in air.   In the present work, the films produced by heating 18/8 chromium-nickel steel appear to carry a greater content of metal (see under " Influence of Temperature on Composition of Films "). Further information is clearly required concerning the content of free metal in films produced by polishing as distinct from films produced by heating in air.

† See first footnote on following page.

equivalent oxygen content as measured by weight-increment. The stripping and subsequent examination of the film were carried out according to the present technique, and satisfactory quantitative agreement was obtained between calculated and observed amounts of nickel.* The results from two of the alumina-polished specimens in which a determination of nickel in the film was possible indicated that the nickel/iron ratio in the film was just equal to that in the steel; on the other hand, this ratio was not realised in the films from the other two alumina-polished specimens, nor in the film from the abraded specimens of Series I., where the iron content was sufficiently high for nickel to have been determined had the metallic ratio been maintained. It follows that, whilst the absence of any appreciable enrichment of nickel in the film is quite definite, the evidence does not warrant any conclusion as to the actual proportion of nickel that passes into the film. No case has been found in which the ratio of nickel to iron in the film is measurably greater than that in the metal; in several cases it is less.†

Relative Thickness of Films.

An estimate of the thickness of the film before stripping was obtained from the total oxide content, assuming Fe_2O_3, Cr_2O_3 and Al_2O_3 to have densities of 5·1, 5·2 and 4·0,‡ from which the respective contributions to the total volume were derived. The values of film thickness (in Ångstrom units) as given in Table I., column (1), were calculated on the apparent area of the specimen, " thickness " being regarded as the mean of the intercepts made by the film on lines normal to the general plane of the surface. If allowance be made for the greater real area (" thickness " then being regarded as the mean of the intercepts made by the film on lines normal to *small elements* of the surface), it is evident that correspondingly smaller values, approximating more closely to the true thickness of the film, will result. This has been attempted in column (2), where the factors applied to convert apparent to real area are those due to Erbacher,[8] namely, 2·5 for abraded, and 1·7 for polished surfaces. Although individual thickness values must be regarded as approximations only, the relative values demonstrate clearly the influence of polishing on film thickness, the film on the most highly polished specimens being at least twice as thick as that on abraded surfaces. (It is probable that a more accurate knowledge of real/apparent area relationships would reveal a greater differentiation in film thickness between the low-grade and high-grade polish.)

Influence of Polishing Material on Composition of Films.

In Series II. two groups of specimens were given as nearly as possible an identical degree of polish by means of alumina and chromic oxide, respectively. Considering specimens polished by alumina (Nos. 30 and 31), it is clear from Tables I. and II. that an appreciable amount of alumina has been forced into the surface during polishing and has become an integral part of the surface film. At the same time the thickness of the film has

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* The agreement obtained was precisely consistent with a formula of NiO for the nickel oxide removed. This confirms electron diffraction evidence for the constitution of the oxide film *in situ* on heated nickel.[7] On chromium (700° C.) Miyake[6] found Cr_2O_3, and on Nichrome (700–900° C.) $NiO.Cr_2O_3$. There are grounds, therefore, for representing as NiO the small amount of nickel oxide found in the stripped film in the present work.

† It is noteworthy that Miyake,[6] in his electron-diffraction study of films *in situ* on heated surfaces of iron, chromium, nickel and their alloys, found in the case of iron-nickel alloys a complete absence of nickel in the film, which consisted of Fe_2O_3. On the other hand, Nichrome gave a film of " pure $NiCr_2O_4$."

‡ Values taken from International Critical Tables.

considerably increased (approximately double the thickness of the high-grade-polish film of Series I.) and with it the content of iron oxide.   Both film thickness and iron oxide content are also considerably greater than (the latter approximately double) the values for the corresponding chromic-oxide-polished specimens.   The increased thickness may be in part an effect of temperature (*vide infra*), since it is possible that in the endeavour to obtain a polish equal in brightness to that on specimens polished with chromic oxide, a greater amount of work was expended with consequent greater rise of surface temperature.   The marked reduction in chromic oxide content as compared with the films from chromic-oxide-polished specimens is consistent with the displacement of chromic oxide by the intrusive alumina.   This is illustrated by the percentage values in Table II. Thus, considering films from chromic-oxide-polished specimens, the content of Cr_2O_3 is in each case 90%, in agreement with each of the high-grade-polish films of Series I.   For the reasons already discussed, it is unlikely that this content was appreciably influenced by the use of Cr_2O_3 in polishing, and the value of 90% is almost certainly characteristic of the high degree of polish.   It would appear that the rate of supply of chromium from the metal is sufficient to maintain the concentration of chromic oxide in the film at the maximum value in the neighbourhood of 90%; this value is therefore not exceeded when chromic oxide is also supplied extraneously.*   On the other hand, when alumina is forced into the film from outside, the concentration of chromic oxide is necessarily reduced. In fact, it is reduced (Table II.) by a greater amount (about 42%) than the amount (about 34%) of alumina taken up, the difference being due to a simultaneous increase of ferric oxide.†   This may be brought about by a greater solubility of Fe_2O_3 in Al_2O_3 as compared with Cr_2O_3, but this is speculative in the absence of information on the mutual solubilities of the several oxides in the flowed layer.

Influence of Temperature on Composition of Films.

For the very limited experiments on the influence of temperature (results under *C* in Tables I. and II.), specimens having the low-grade polish Ic were heated in air in a thermostatically controlled furnace at 500° C. for 17 hr.   As the mean increase of weight due to oxygen taken up during heating (4·4 µg. per sq. cm.) fell considerably short of the oxygen increase calculated from metal content, it may be concluded that an appreciable amount of iron or chromium (or both) is present as metal; some of the iron, moreover, may be present as FeO.   Further work is necessary to settle these points.   From the present point of view, the outstanding feature is that, although the thickness of the film has increased by some 500%, the chromium/iron ratio has fallen by about 50% of its original value.   Making due allowance for the arbitrary temperature conditions (moderate temperature with prolonged heating period), it is of interest to compare the effect of this heat treatment with the influence of polish, which, besides a considerable rise of surface temperature, must involve a certain amount of surface flow.   In each case there is enrichment of chromium in the film as compared with the metal, but it is much more marked for polishing than for simple heat treatment.   This is shown by the relevant data of Table I., *C*.   Thus, heat treatment has produced a film of

* Naturally, some of the chromic oxide found in the film from the chromic-oxide-polished specimens may be expected to come from the polishing material, but in that event the contribution from the oxidation of chromium in the steel must be correspondingly reduced.

† This statement assumes that iron is present entirely as Fe_2O_3; an alternative explanation is obviously that some is present as metallic iron or as FeO (*see* under "Composition of Films and Surface Condition").

thickness greater than 200 Å. with a chromium/iron ratio of about 2·0, whereas polishing alone (*A*, Nos. 17 and 19) yielded a chromium/iron ratio some 4 times greater in a film of only a fifth of the thickness. The results suggest that the effects produced by polishing, *e.g.*, a high chromium/iron ratio in a very thin surface film, cannot be explained in terms of surface temperature alone. No doubt the far higher temperatures reached transiently in the process of polishing would facilitate diffusion in the surface layers. There would seem to be little doubt, however, that the major distinction is that of surface flow in the one case and its absence in the other, the increased mobility allowing greater freedom for the competing metals to take up oxygen according to their respective reactivities. It is significant that the order (qualitatively) in which the oxides appear in the film is that of the corresponding free energies of formation, *viz.*, Cr_2O_3, -249; Fe_2O_3, -179; NiO, -52.* A quantitative agreement with this order would not be expected, since other factors must intervene to control the oxidation rate. It is suggested that the great predominance of Cr_2O_3 may be accounted for by the selective oxidation of chromium according to the principle described by Thomas and Price.[10, 11] This depends on the supply of atmospheric oxygen at the metal surface being severely restricted, as, for example, when an alloy is heated in an almost inert atmosphere; the oxidation of the more reactive constituent is thereby favoured even when it is present in minor proportion in the alloy. In the polishing of stainless-steel surfaces it may well be that such conditions will operate, bearing in mind the intimate contact that must be maintained between the metal and the polishing medium, especially during the periods when surface flow is taking place.

Effect of Polishing and of Polishing Material on Electrode Potential of Surface Film (in situ).

Electrode potential measurements on the stainless-steel sheet, immersed in $N/200$ sodium chloride solution exposed to air, have been used to com-

TABLE III.—*Influence of Surface Film on Electrode Potential (in N/200 NaCl).*

Specimen Number.	Pre-Treatment of Specimen.	Potential (N/10 Calomel Scale). MV. after—				
		1 Min.	1 Hr.	1 Day.	100 Days.*	17 Months.*
P14	Polished. High-grade, I*d*.	+ 16	+ 32	+ 6	+28	...
P15	Polished and stripped.	− 67	−191	−97 †	+10	...
P41	Polished with Al_2O_3.	−127	−136	−76	...	+118
P42	Polished with Cr_2O_3.	− 41	− 41	−12	...	+146

* End of experiment.   † Period of 2 days.

pare the passive properties before and after stripping the surface film, and to examine differences of passivity produced by different polishing methods. Specimens measuring $5·0 \times 2·5$ cm. from sheet prepared by high-grade polish I*d* were coated along the edges and over the upper 3·5 cm. length with a gutta-percha/paraffin-wax mixture. In each experiment the specimen was held vertically from above by a crocodile clip and immersed to a depth of 3·0 cm. in 300 ml. of solution; the exposed surface of the metal was therefore totally immersed between depths of 1·5 and

* Values (expressed in kilogramme-calories) are those given by M. de Kay Thompson.[9]

3·0 cm. The solution was contained in a cylindrical glass vessel, 9·4 cm. in dia., covered by a filter-paper sheet, and placed inside a draught shield. The temperature was moderately constant, usually between 17° and 19° C. Potentials were measured against an $N/10$ calomel electrode, connected only during the period required for measurements through a bridge of $N/200$ sodium chloride. Liquid-junction potentials were neglected, being constant throughout.

Typical results are summarised in Table III. and in Figs. 2 and 3.
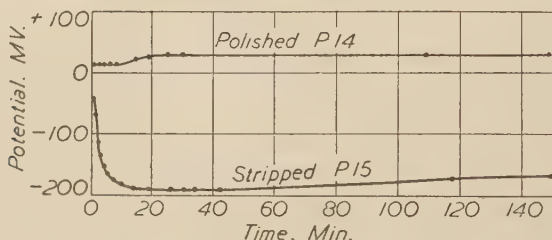
Fɪɢ. 2. -Potentials ($N/10$ Calomel Scale) of Polished and Stripped Surfaces of 18/8 Chromium-Nickel Steel in $N/200$ NaCl.

Comparing $P14$ and $P15$ (Fig. 2), the stripped surface was markedly less passive than the polished surface, although the difference diminished with time after one hour. The rapid fall in potential of the stripped specimen during the first 20 min. is in striking contrast with the slight rise and subsequent steady values of potential recorded for the polished surface. Results from $P41$ and $P42$ (Fig. 3) show the more passive behaviour of steel polished with chromic oxide as compared with that polished with alumina. Although in both cases the surface became more
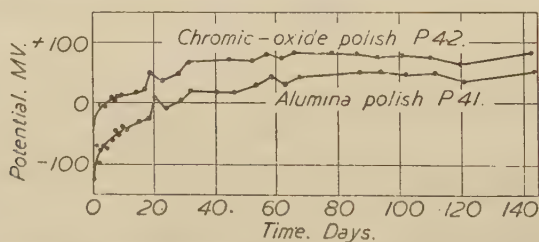
Fɪɢ. 3.—Influence of Polishing Material on Potential ($N/10$ Calomel Scale) of 18/8 Chromium-Nickel Steel in $N/200$ NaCl.

passive with time, the difference between the two persisted for at least 17 months.

Summary.

Using a technique previously described and several types of surface finish (abraded with emery and industrially polished), the surface oxide-film has been stripped from chromium-nickel (18/8) austenitic stainless steel. From the results of chemical analysis of the film, estimates have been made of its thickness and composition in relation to the influence of polish and of the polishing material.

The thickness of the film as measured by total oxides present (Cr_2O_3, Fe_2O_3, NiO) increases with the degree of polish; approximate values are given for " apparent " and calculated " real " surface areas.

For all methods of preparation there is a marked enrichment of chromium in the film as compared with chromium in the underlying steel. This enrichment increases with the degree of polish. In the steel the ratio of chromium to iron (by weight) is 0·24; in the film it is approximately 0·7 for abraded surfaces, 3·8 for surfaces of moderate brightness and approaches 9·0 for the most brightly polished surfaces. The concentration of chromic oxide in the film correspondingly increases to a maximum and fairly uniform value of 90% by weight, the balance being mostly ferric oxide.

No enrichment of nickel in the film as compared with that in the steel has been observed. In two cases the initial " metal ratio " was approximately just realised in the film, the concentration of nickel then being equivalent to the presence of about 2% of NiO.

When the final polishing is carried out with alumina, this substance is introduced into the film to the extent (in the examples investigated) of approximately one-third of the total weight of oxides in the film. This has the effect of depressing the concentration of chromic oxide to a somewhat greater extent, the balance being made up by an increase in the content of ferric oxide.

The use of chromic oxide in the final stages of polishing, although giving a very fine polish and a rather thicker film, does not increase the concentration of chromic oxide in the film beyond approximately 90%, which is characteristic of highly polished surfaces.

Electrode potential measurements on specimens immersed in $N/200$ sodium chloride solution have confirmed that a surface from which the film has been removed is considerably less passive that the polished surface, though the difference diminishes with prolonged immersion. They have also shown that specimens polished with chromic oxide are markedly more passive (more " noble ") than specimens polished with alumina; it is believed, however, that this is due to the defection from the normal content of chromic oxide in the alumina-polished surfaces.

It is suggested that the enrichment of chromium (as chromic oxide) in the surface film and its dependence on the degree of polish are associated with surface flow during polishing, which serves to bring the metallic constituents into more intimate contact with available oxygen. It is considered that the oxidation rate is controlled partly by the free energies of formation of the respective oxides and probably to a greater extent by selective oxidation arising from the restriction of oxygen at the surface between the metal and the polishing material while surface flow is taking place.

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THE MAGNETISATION OF POLYCRYSTAL-LINE IRON AND IRON-SILICON ALLOYS.*

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Summary.

During the immediate pre-war decade substantial advances were made in the domain theory of ferromagnetism, but investigational work on carefully prepared and highly purified single-crystal speci-mens often revealed a disappointing lack of accord between theory and observation.

In view of the importance of the subject in its relation to im-provements in the ferromagnetic performance of the polycrystalline electrical sheet steels which constitute the essential constructional foundation of electrical generators, motors and transformers, a new survey has been made of the competency of the domain theory to account for the observed characteristics of such material.

The general conclusion arrived at is that the basic theory, in a very simple form, can provide reliable guidance for industrial effort, but that certain as yet unexplained but inherently significant dis-harmonies between theory and observation are common to labora-tory single crystals and to commercial polycrystalline aggregates.

The survey has also yielded a new method of analysis of the technical magnetisation curve, which may be of general utility in assessing variations in the distribution of lattice orientation in ferromagnetic specimens.

PART I.—INTRODUCTION.

No longer ago than 1930, after a half-century of investigation largely inspired by his own work and teaching, Ewing [1] was still able to describe as an " attractive tangle " what Tyndall once referred to as " the revulsive phenomena of the magnetic field "; and even ten years later it could be recorded that so far as the out-standingly important magnitudes of the alternating hysteresis loop are concerned " the quantitative theory is still in its infancy." [2] Against this, it was possible to affirm in 1938 that " the theory of magnetism has made great strides; " [3] and since then some very valuable additions have been made to the available experimental evidence. [4–7]

Much of this recent evidence is in generally encouraging agree-ment with the fundamentals of the modern theory, but there have also been established some unexpected complexities and discouraging contradictions which have not tended to simplify the practical interpretation and application of the results of much thought and labour. It is, to say the least, a little bewildering to those who seek guidance in the industrial task of improving the magnetic performance of commercial polycrystalline soft ferro-

magnetics to find themselves confronted with the observation that, on a highly purified and very effectively heat-treated single iron crystal, it is possible to record a maximum permeability some hundred times greater than any normal value, but disturbingly coupled with a measured coercive force of an irreconcilably high order.[8]

Other disappointing difficulties have been similarly strangely related to the behaviour of equally carefully prepared laboratory specimens, which at first sight would be expected to reveal the best agreement between theory and observation; and some of the later evidence appears disconcertingly to support the view that " an explanation of the properties of a complex ferromagnetic material can hardly be given when there are still difficulties in interpreting the properties of a relatively simple iron crystal." [9]

Nevertheless, the nature of many of the experimental disharmonies has increasingly provoked the conception that they may result from the operation of factors which can literally be described as superficial, and has thus encouraged the undertaking of a new survey of the general position from first principles with the main objects of determining :

(a) The degree of success with which simple but intrinsically appropriate derivations from the formal theory can be applied to predict the qualitative behaviour of the soft ferromagnetic polycrystalline sheet aggregates which find such important industrial applications in the construction of electrical generators, motors and transformers; and

(b) the manner in which such primary derivations from the theory need to be modified in order to achieve a " model " of polycrystalline magnetisation with such a quantitative response as will render it acceptable as a guide to the most profitable lines of practicable attack on the problem of improving the magnetic performance of such commercial aggregates.

The adopted method of approach to these objectives has been first to establish the simplest possible framework of polycrystalline magnetisation permitted by the theory; and then to determine the manner in which, without violence either to secure principles or to established facts, it is legitimate to modify this framework so as to eliminate or minimise any outstanding discord between theory and observation.

The broad results of this analysis are here reported; and it can at once be said that they appear to provide overwhelming support for the opinion expressed shortly before the war[3] that " the theory of magnetism has now reached a stage where it ought to be a guide " to technical advances.

The methods of the investigation have also led to some specific conclusions which appear to embody elements of novelty of possible general interest and utility; but the adequate presentation and

discussion both of methods and results will necessitate a preliminary sketch of the selected theoretical essentials on which the survey has been based. The subject-matter is not widely familiar, and it is imperative that there shall be no uncertainty concerning primary assumptions.

This theoretical outline, as given in Part II., makes use of certain conceptions which are not rigidly orthodox. From the puristic standpoint a measure of over-simplification may thus have been introduced, but the everyday evidence does not suggest that any such unfamiliar simplicity of treatment has led either to indefensible heresy or to major error.

The ground to be covered is extensive, and much of the discussion will necessarily be exploratory and of a nature which involves adherence to the Faraday principle that even if, on many points, " it is impossible to speak . . . without committing oneself beyond what present facts will sustain . . . it is equally impossible, and perhaps would be impolitic, not to reason upon (them)." [10]

PART II.—THE DOMAIN THEORY OF FERROMAGNETISM.

(1) *Symbols, Definitions and Fundamental Relationships.*

That the formal theory of ferromagnetism has indeed made great strides during the past decade or so is evidenced by the fact that it now seems possible to present its practical essentials almost wholly in non-mathematical form, using only a few transparent equations and the elementary mensuration of the simple cube. To assist brevity in exposition, however, familiarity will be assumed with the orthodox symbols and definitions listed in the Appendix, which also summarises for convenient reference some unfamiliar symbols which are introduced in the course of this paper.

(2) *Crystallographic Notation.*

Iron and iron-silicon alloys, in their ferromagnetic states, are examples of crystalline matter with a body-centred cubic space-lattice; and the ferromagnetic phenomena to be discussed are markedly directional with respect to the basic geometry of the atomic arrangement. The following simple " Miller " notation will be used in referring to directional properties :

Cubic Crystal Direction.				Notation Used.
Parallel to cube edge	.	.	.	[100] direction.
Parallel to cube face diagonal		.	.	[110] direction.
Parallel to internal cube diagonal	.		.	[111] direction.

(3) *The Ferromagnetic Domain Structure.*

" Solids are rarely, if ever, perfect crystals. . . . A crystal consists of small domains or crystallites in which the atoms form a perfect lattice system." [11] These statements are of general appli-

cation to all crystals, whether ferromagnetic or not; but in the case of a ferromagnetic specimen uninfluenced by any external magnetising field all the constituent domains of the specimen (whether a single crystal or a polycrystalline aggregate) are to be regarded as at all times in a condition of spontaneous magnetisation* to the saturation intensity appropriate to the temperature of the specimen, this condition of spontaneous magnetisation being homogeneous, like the assumed perfection of the atomic lattice itself, throughout any given domain. In the immediate neighbourhood of internal domain boundaries and of crystal surfaces, whether internal or external, there will be transition regions of varying thickness in which this postulated homogeneity obviously cannot exist.

For a ferromagnetic specimen of given composition at a given temperature, the saturation intensity of magnetisation can be regarded as a structure-insensitive constant, the magnitude of which will be independent of the mechanical condition of the specimen.

(4) *The Demagnetised State.*

The demagnetised state of a ferromagnetic specimen is the state in which the externally measurable value of I is zero when H is also zero. This zero external value of I will necessarily involve an internal distribution of spontaneous domain magnetisation of such a nature that no resultant value of I remains available for measurement by external means.

The saturation intensity of spontaneous domain magnetisation is a vector quantity with direction as well as magnitude; and it will be seen later (section (11)) that there are good reasons for believing that in the demagnetised state least-energy expectations are realised to the extent that the alignment of the directions of homogeneous domain magnetisation can be broadly conceived as distributed between the six possible [100] directions of the cubic space-lattice. Such directions are also known to be, for a body-centred cubic structure, the directions of " easiest " magnetisation under the influence of an external magnetising field.

From this it follows that the domain structure of a body-centred cubic ferromagnetic in the demagnetised state can be idealised as consisting of an aggregate of groups of six saturated domains as pictured (in two dimensions only) in Fig. 1, all six domains in each domain-group being equal in volume. (In domain No. 5 the direction of spontaneous magnetisation is perpendicular to the plane of the paper, downwards; in domain No. 6 it is in the parallel upward direction.)

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* The orthodox term spontaneous will be used throughout in referring to domain magnetisation which exists without external incitement. Although this term is derivatively unassailable, it has a looser everyday meaning which often gives rise to misconception; and it would seem to be open to question whether it could not well be replaced by some less confusing alternative, such as inherent or specific or—perhaps most expressively—indigenous.

It should be noted that, although the discussion is here being temporarily simplified by assuming that in any idealised demagnetised domain-group all the six constituent domains will be of equal volume, this is not an essential assumption, since the demagnetised state will always be externally registered so long as there is vectorial equality of volume of parallel and anti-parallel magnetisation along each of the basic [100] crystal directions.   Further, all the domain-groups in the specimen need not themselves be of equal volume; and, as emphasised in Fig. 1, no assumption need be made concerning domain shape.

FIG. 1.—Idealised Domain-Group; demagnetised state.

This general conception of the ferromagnetic domain structure is much more than an artificial statistical basis for academic speculation; that there exists some sort of corresponding physical reality is evidenced, but far from solely, by the Bitter patterns of stray surface fields, on which much work has been done by Elmore.[12, 13]

It will be clear that the physical existence of a domain structure provides direct evidence of basic crystal imperfections; * and it is reasonably certain that " the normal state of a ferromagnetic body in the absence of any external field would be complete saturation parallel to one of the directions of easiest magnetisation. The unmagnetised state is essentially unnatural to a perfect, uniform, ferromagnetic crystal from which all extraneous influences have been removed." [15]   Such an " unnatural state " clearly cannot be the state of least energy to which all physical systems tend when not otherwise constrained; its internal equilibrium must therefore be dynamically unstable; and during that part of the process of magnetisation which is of the greatest practical interest, it is the function of an external magnetising field to increase that instability and so conduce to the attainment of conditions of least energy throughout the ferromagnetic lattice structure.

(5) Magnetostriction.

Above a characteristic temperature, called the Curie point, a given (ideal) ferromagnetic will lose its capacity for the spontaneous magnetisation of its constituent domains.   The state of spontaneous domain magnetisation which exists in a demagnetised ferromagnetic at room temperature is progressively acquired during the process of cooling from the Curie temperature.   The saturation intensity appropriate to any given temperature below the Curie point in-
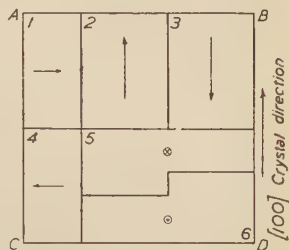
* A usefully concise general discussion of crystal imperfections, with detailed references, has recently been given by Hume-Rothery.[14]

H

creases very rapidly during the earlier stages of cooling, but much
more slowly during the later stages. For unalloyed iron the Curie
point is of the order of 770° C.; but for a 4% iron-silicon alloy it has
a lowered value of the order of 730° C.

It has long been known that the process of magnetisation of a
demagnetised ferromagnetic is accompanied by dimensional changes
called the Joule effects of magnetostriction. In polycrystalline
iron and iron-silicon alloys, these effects consist in an elongation
of the specimen along the direction of the applied magnetising field
and in a simultaneous contraction transverse to that direction, the
relative magnitudes of elongation and contraction being such as to
involve no material change in the volume of the specimen.

The importance of magnetostrictive dimensional changes in the
analysis of the magnetisation process arises from the following
established propositions :

(a) That the spontaneous domain magnetisation acquired
during cooling from the Curie point will be directed, in any
given domain, along one of the [100] crystal directions of easiest
magnetisation ;

(b) that the acquisition by any given domain, during cooling
from the Curie point, of spontaneous magnetisation to the room-
temperature saturation intensity I_s will be accompanied by a
magnetostrictive elongation of that domain along the favoured
[100] crystal direction of domain magnetisation ;

(c) that the magnitude of this magnetostrictive elongation
(per unit of domain length) is a physical constant for any given
ferromagnetic ; and

(d) that if, in Fig. 1, the demagnetised direction of magnetisa-
tion of a domain such as domain No. 1 is changed into parallel-
ism with that of a domain such as domain No. 2, the original
magnetostrictive elongation of domain No. 1 parallel to AB
will be changed into a magnetostrictive elongation parallel to
CA the magnitude of which will be determined by the character-
istic value of the magnetostrictive constant.

The magnitude of the characteristic magnetostrictive constant
for a body-centred cubic ferromagnetic is conventionally assessed by
measurement of the elongation per unit of length which occurs when
an initially demagnetised single crystal is magnetised to the saturation
intensity I_s along a [100] direction; this magnitude is called the
saturation magnetostriction coefficient and is commonly symbolised
as λ_0 (but sometimes, more precisely, as λ_{100}) ; its value for unalloyed
iron is generally accepted as being of the order of 20×10^{-6}. [15] It is,
however, necessary to bear in mind that the physical meaning of
such an externally measured value of λ_0 will depend on the demag-
netised distribution of the internal directions of domain magnetisa-
tion (*see* section (26)).

It follows from (d) above that all changes in the initial directions of demagnetised domain magnetisation, other than simple reversals, will involve the performance of physical work against the mechanical resistance of the lattice structure, and that the amount of energy thus expended will depend directly on the value of λ_0, and also on the elastic properties of the lattice (*see* section (7) (a)).

(6) *The Mechanisms of Magnetisation.*

With the idealised demagnetised domain-group of Fig. 1, the application of a steadily increasing external magnetising field parallel to CA will ultimately result in the demagnetised directions of spontaneous magnetisation in all the domains becoming vectorially parallel to the demagnetised direction of spontaneous magnetisation in domain No. 2. The domain-group will then be magnetised to the saturation intensity I_s along the field direction CA.

This process of magnetisation to saturation will clearly involve two entirely different kinds of response within the lattice structure of the domain-group. In domains Nos. 1, 4, 5 and 6 the attainment of vectorial parallelism with domain No. 2 will involve 90° turns of demagnetised domain magnetisation associated with magnetostrictive dimensional changes effected against the mechanical resistance of the lattice. No such dimensional changes will be involved, however, by the 180° reversal by which domain No. 3 attains vectorial parallelism with domain No. 2. It is therefore to be expected that both the mechanism of the magnetisation process and the quantitative relationships between I and H will differ markedly for these two very different sets of physical conditions.

The mechanism of magnetisation by 90° turns can be pictured as one in which domains with demagnetised directions of spontaneous magnetisation favourably oriented with respect to the direction of the applied field will increase their volume, as the field strength increases, by a continuous process of " nibbling growth " across the 90° " walls " of the domain structure, very much in the same way as increasing thermal agitation of a plastically deformed crystal aggregate can result in the growth of energetically favoured crystals at the expense of less favoured neighbours ; whereas the mechanism of magnetisation by 180° reversals can be better likened to the discontinuous or " explosive " changes that occur in the internal film structure of a multi-cellular soap-bubble when two cells suddenly become one. Both the suggested analogies fail, however, in the respect that the changes in the worked crystal aggregate and in the liquid film structure are alike irrevocable, whereas it is always possible, by suitable manipulation of the external magnetising field, to restore a given ferromagnetic specimen very nearly to its initial demagnetised state and then to repeat the magnetisation process with very nearly the same quantitative results ; and this revocability and reproducibility of the process of magnetisation clearly

constitute strong presumptive evidence of the physical permanence
of the initial demagnetised domain structure.

If the direction of the applied field deviates from a [100] crystal
direction, the process of magnetisation by 90° turns or 180° reversals
will proceed qualitatively (but not quantitatively) in exactly the
same way until the demagnetised directions of domain magnetisa-
tion have all been vectorially aligned along [100] crystal directions
which make the minimum angle with the direction of the applied
field, the whole process being subject only to the condition that
there shall be no resultant value of I transverse to the field direction.

With the idealised conditions of Fig. 1, if the external field is
applied along the [110] crystal direction DA, the process of magnetisa-
tion by a combination of 90° turns and 180° reversals will stop when
the demagnetised directions of spontaneous magnetisation in all the
six domains have attained parallelism either with the [100] crystal
direction CA, or with the [100] crystal direction BA, with equal
volumes vectorially parallel to each of these two directions.   The
externally measured resultant value of I along the field direction
DA will then be $I_s/\sqrt{2}$.   Similarly, if the field is applied along a
[111] crystal direction, the completion of the 90° turns and 180°
reversals will yield a resultant value of I, along the field direction,
of magnitude $I_s/\sqrt{3}$.

From this it follows that when the field direction deviates from
a [100] crystal direction, the completion of the 90° turns and 180°
reversals will still leave a gap between the externally-measurable
value of I and the potential saturation intensity I_s.   This gap can
be bridged only by the operation of a third mechanism of magnetisa-
tion, which consists in the rotation of the internal directions of
domain-group magnetisation into vectorial parallelism with the
external field direction.   This third mechanism of magnetisation
will involve a constrained departure from the lattice conditions of
least energy attained by the completion of the 90° turns and 180°
reversals, and will be subject to very different laws from either of
the other two.

(7) *The Stages of Ideal Magnetisation.*

(a) *Initial Magnetisation.*

When an idealised demagnetised domain-group (Fig. 1) is sub-
jected to the influence of an external magnetising field applied along
a [100] crystal direction such as CA and gradually increased from
zero strength, the initial processes of magnetisation can be regarded
as occurring by the mechanism of 90° turns in domains in which
the demagnetised directions of spontaneous magnetisation are
oriented, with respect to a favourably-oriented domain such as
domain No. 2, similarly to domain No. 1 ; and it can be shown
that for such conditions the quantitative relationship between I
and H should obey some such law as :

$$I/H = k_0 = \text{initial susceptibility} = aI_s{}^2/\lambda_0Z_i \quad . \quad . \quad . \quad (1)$$

where a is a variable fraction depending (i) on the internal surface area per unit of volume competent to stimulate the 90° turns of nibbling growth and (ii) on the direction of the applied field with respect to favourable [100] crystal directions; Z_i is the mean internal lattice stress which opposes the magnetostrictive dimensional changes associated with 90° turns; and λ_0 is the saturation magnetostriction coefficient as defined in section (5).

Equation (1) is a general form of the relationship arrived at by Becker and Kersten for certain specific conditions of magnetisation.[16]

The term $\lambda_0 . Z_i$ in equation (1) is directly related to the work done per unit of volume of the lattice in achieving 90° turns of spontaneous domain magnetisation. It will be a lattice constant and will have a minimum value when there is no internal stress in the lattice other than that due to the effects of magnetostrictive dimensional changes during cooling from the Curie point; such conditions will give $Z_i = \lambda_0 . E_0$, where E_0 is Young's modulus for [100] crystal directions.

The precise nature and quantitative influence of the lattice factors which govern the actual magnitude of Z_i have not yet been established, but any increase in the general intensity of internal boundary disturbance will naturally be expected to increase Z_i. This expectation is confirmed by the known effects of plastic deformation and of precipitation-hardening on the observed values of k_0.

Equation (1) shows that the initial relationship between I and H should tend to be linear, as experimentally established by Rayleigh,[17] see also Ewing.[18]

(b) *180° Reversals.*

The initial linear stage (in well-annealed material) will be of short duration; and when H has attained, along the assumed [100] crystal direction of external magnetisation, a critical field strength $H_{0[100]}$, the instability of the lattice equilibrium at the 180° walls of the domain structure will be increased to the point at which they break down; and if the distribution of instability is uniform throughout the lattice, all the 180° reversals of anti-parallel domain magnetisation will take place with H remaining virtually unchanged at the critical strength $H_{0[100]}$. The resulting sudden jump in the value of I is usually referred to as a Barkhausen jump or discontinuity, in recognition of the physicist who first made the phenomenon audible by connecting a telephone to a magnetising circuit.

The magnitude of the critical field strength $H_{0[100]}$ will clearly depend on the domain-boundary conditions across 180° walls, and interstitial impurities and plastic strain of the lattice must adversely affect it (*see* section (17)). It will also be seen later that it is one of the factors which govern the observed value of that hitherto somewhat obscure quantity familiarly known as the coercive force (sections (30) and (34)).

The Barkhausen jumps are not instantaneous.   The experimental evidence indicates that they should be imagined as starting from nuclei (which can be thought of as local breaches in 180° walls), and as being propagated or exploded through the lattice with a finite velocity of the rather surprisingly low order of a few hundred feet per second.

(c) *Completion of* 90° *Turns.*

The brief initial stage of nibbling growth will have made but relatively small progress across the 90° walls of the domain structure, and with the 180° reversals cleared out of the way the 90° turns will proceed to completion.   Since the lattice conditions governing this stage must be basically of the same nature as those which govern the initial stage, it seems legitimate to assume that the qualitative relationship between I and H will also be generically similar to that expressed by equation (1), and that this stage, like the initial stage, will (ideally) exhibit no discontinuities.

The simplifying conception here introduced that the bulk of the 90° turns will follow the completion of the 180° reversals is perhaps not generally accepted; but the ingenious measurements made by Bozorth and Dillinger [19] of the volumetric distribution, with respect to H, of the Barkhausen discontinuities, " definitely supports the view that in low fields on the average all the magnetic vectors change by very nearly 180°. . . ." [20]   This view is also strongly reinforced by direct measurements of magnetostrictive dimensional changes [7, 15] (*see also* sections (33) and (37)).

(d) *Approach to Saturation.*

In any idealised domain-group, with magnetisation along a [100] crystal direction, the saturation intensity I_s will be reached when the 90° turns have been completed.

When the direction of the applied field deviates from a [100] crystal direction, the quantitative relationship between I and H during the final rotational process of approach to saturation will be determined (i) by the magnitude of the angular deviation and (ii) by the magnetic anisotropy constants of the specimen.

The anisotropy constants can be experimentally determined in a number of ways; and by reference to soundly established energy equations the behaviour of a ferromagnetic during the final stage can be calculated with results in satisfactory agreement with observation.   The present discussion will not, however, be directly concerned with the final stage of the magnetisation process, except in so far as it will make use of the familiar fact of observation that over this stage the rate of increase of I with H is virtually identical in polycrystalline ferromagnetics for which the elastic constants and distribution of crystal orientation are substantially similar, even where there exist quite wide variations in chemical composition and mechanical condition.

PART III.—THE VIRGIN MAGNETISATION CURVE—SINGLE CRYSTALS.

(8) [100] *Crystal Direction—Theoretical.*

According to the principles of Part II. the virgin magnetisation curve of a single crystal with the applied field along a [100] crystal direction should take the form $OABC$ represented by curve I. in Fig. 2. In this curve the initial stage OA has been exaggerated with respect to the rest of the curve, and the increment of I along OA is to be regarded as relatively small.
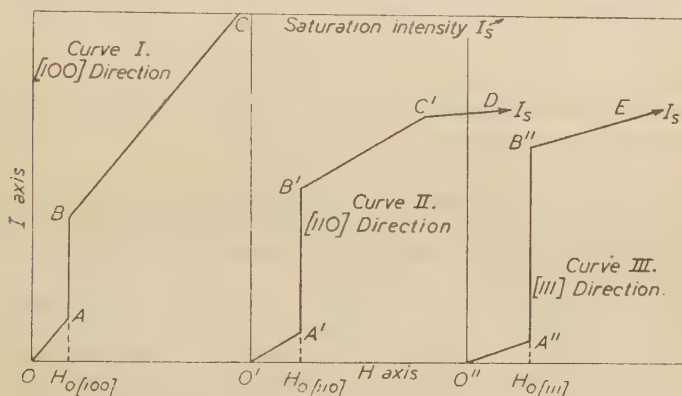
FIG. 2.—Ideal Magnetisation Curves for Single Crystal.

The stage AB represents the Barkhausen jump in the value of I which results from the simultaneous occurrence, throughout the crystal, of the 180° reversals at the critical field strength $H_{0[100]}$. The stage BC represents the completion of the 90° turns. It will be temporarily assumed that BC can be drawn parallel to OA (the probable invalidity of this assumption is discussed in section (20)).

It will also be provisionally assumed that there is an equal distribution of demagnetised domain orientation along each of the six possible [100] crystal directions. Under such conditions the increment of I along AB will be $I_s/3$; and the increment of I along BC will be $2I_s/3$, thus yielding the saturation intensity I_s at C. Any further increase in H beyond its value at C will simply result in the magnetisation curve following the horizontal corresponding to I_s.

(9) [110] *Crystal Direction—Theoretical.*

With the applied field along a [110] crystal direction, the single-crystal magnetisation curve should be of the form $O'A'B'C'D$ shown in curve II. of Fig. 2.

In this case the duration and slope of the initial stage $O'A'$ can

be determined by evaluating the effective strength, along a [100] crystal direction such as BA or CA in Fig. 1, of any given field strength applied along a co-planar [110] crystal direction such as DA; and then evaluating (i) the value of I which this resolved field strength produces along the [100] crystal direction and (ii) the externally measurable value of this internal I along the [110] crystal direction of external magnetisation. It is a simple case of resolving twice along directions which make an angle of $45°$ with each other; and the final result will be that, if $I_{0[100]}$ is the value of I at point A in Fig. 2, curve I., the co-ordinates of the point A' in curve II. will be given by :

$$H_{0[110]} = \sqrt{2} . H_{0[100]}$$
$$I_{0[110]} = I_{0[100]}/\sqrt{2},$$

whence the initial susceptibility $k_{0[110]}$ for [110] conditions of magnetisation will be given by :

$$k_{0[110]} = \frac{I_{0[110]}}{H_{0[110]}} = \frac{I_{0[100]}/\sqrt{2}}{\sqrt{2} . H_{0[100]}} = \frac{k_{0[100]}}{2} \quad . \quad . \quad (2)$$

In Fig. 2, curve II., the stage $A'B'$ represents the Barkhausen discontinuity at the critical field strength $H_{0[110]} = \sqrt{2} . H_{0[100]}$. The stage $B'C'$ represents the completion of the $90°$ turns. It will be temporarily assumed, as for BC in curve I. (but again with reserved discussion of the probable invalidity of the assumption), that $B'C'$ can be drawn parallel to $O'A'$.

Consideration of Fig. 1 will show that in curve II. of Fig. 2 the increment of I along $A'B'$ will be $\frac{2}{3} . I_s/\sqrt{2}$; and that the increment of I along $B'C'$ will be $\frac{1}{3} . I_s/\sqrt{2}$, thus yielding a value of I at C equal to $I_s/\sqrt{2}$.

In curve II. of Fig. 2 the continuation of $C'D$ will represent the final stage of approach to the saturation intensity I_s.

(10) [111] *Crystal Direction—Theoretical.*

By reasoning analogous to that used in section (9) it can be shown that :

$$k_{0[111]} = \frac{k_{0[100]}}{3} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

whence, in curve III. of Fig. 2, the critical field strength $H_{0[111]}$ will be $\sqrt{3} . H_{0[100]}$, and the value of I at A'' will be $I_{0[100]}/\sqrt{3}$.

In this curve, $A''B''$ represents the Barkhausen $180°$ jump; and the conditions of cubic symmetry, considered in conjunction with Fig. 1, indicate that the increment of I along $A''B''$, at the critical field strength $H_{0[111]} = \sqrt{3} . H_{0[100]}$, will be $I_s/\sqrt{3}$, and that the stage of completion of $90°$ turns will be absent.

The continuation of $B''E$ will represent the final approach to I_s; the formal theory of the approach stage indicates that the

slope of $B''E$ in curve III. will be somewhat greater than the slope of $C'D$ in curve II., as roughly shown.

(11) *Theory* versus *Observation*.

The as yet unpredictable effects of stray surface fields render it extremely difficult to obtain reliable and consistent experimental data on single-crystal specimens, especially in moderate magnetising fields; but some of the major obstacles have in recent years been skilfully surmounted by Williams,[4] whose measurements on "picture-frame" specimens have not only confirmed the satisfactory agreement between theory and observation recorded by earlier observers for the final stage of approach to saturation [12] (*loc. cit.*, p. 205) but have also strikingly established the validity of the simple argument of section (9), which was apparently first noted by Bozorth,[21] and which leads to the theoretical relationship :

$$k_{0[100]} : k_{0[110]} : k_{0[111]} = 6 : 3 : 2 \qquad . \quad . \quad . \quad . \quad (4)$$

For both weak and strong fields, therefore, there is firm supporting evidence for the broad validity of the basic theory, both qualitative and quantitative; and it is important to note that the experimental verification of equation (4) fully justifies the primary assumption of section (4) that the demagnetised directions of domain magnetisation are all very nearly aligned along [100] crystal directions of easiest external magnetisation.

Over the steep part of the magnetisation curve, which will by hypothesis be chiefly associated with 180° reversals, there is satisfactory qualitative agreement between theory and observation, but this qualitative agreement is marred by serious quantitative discord which does not yet appear to have been resolved; [21] and it will be seen later that similar puzzling discrepancies can be recorded on polycrystalline specimens (section (27)).

PART IV.—THE MAGNETISATION CURVE OF POLYCRYSTALLINE AGGREGATES—THEORY.

(12) *The Ideal Magnetisation Curve—Synthesis.*

As a first step in the present investigation of the competency of the domain theory, as here simplified, to predict the behaviour of a polycrystalline cubic ferromagnetic specimen, consideration will be given to the ideal behaviour of an aggregate of three crystal-groups, each of equal volume, but with their preferential [100] crystal directions of demagnetised domain magnetisation so aligned with respect to the direction of the applied magnetising field as to reproduce, respectively, the conditions of [100], [110] and [111] magnetisation summarised in sections (8) to (10).

With such an aggregate the application of the argument of section (9), which has been validated by Williams' experimental results,

will indicate that the initial susceptibility $k_{0(a)}$ should be given by :

$$k_{0(a)} = \frac{k_{0[100]}}{3} \cdot (1 + \tfrac{1}{2} + \tfrac{1}{3}) = 0 \cdot 61 \, k_{0[100]} \quad . \quad . \quad . \quad (5)$$

This value of $k_{0(a)}$ will therefore determine the slope of OA in Fig. 3.

At point A in Fig. 3 the applied field is to be regarded as having attained the critical strength $H_{0[100]}$ competent to initiate and
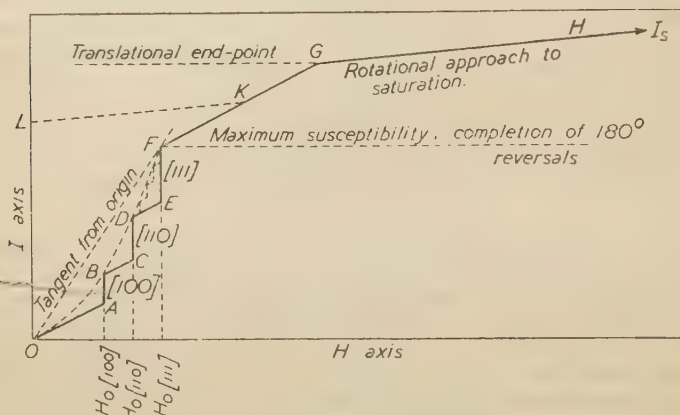
Fig. 3.—Ideal Magnetisation Curve for Polycrystalline Aggregate.

propagate the 180° reversals in the [100] crystal-group of the aggregate ; and with the assumed equality of distribution of crystal-group orientation with respect to the direction of H there will occur a jump increment of I along AB, with $AB = I_s/9$.

As H is increased from its value at B to its value at C, the relatively very small increment of I will be the result of additional 90° turns of continued nibbling growth, and very little error can here be introduced by drawing BC parallel to OA.

At the point C, H will have attained the critical strength $H_{0[110]} = \sqrt{2} \cdot H_{0[100]}$ competent to initiate and propagate the 180° reversals of the [110] crystal-group of the aggregate, and the increment of I along CD will be $\dfrac{\sqrt{2}}{9} \cdot I_s$.

The small increment of I between D and E will again be due solely to additional 90° turns ; and, as for BC, there can be but little error in drawing DE parallel to OA.

At E, H will attain the critical strength $H_{0[111]} = \sqrt{3} \cdot H_{0[100]}$ competent to initiate and propagate the 180° reversals of the [111] crystal-group, and the increment of I along EF will be $I_s/3\sqrt{3}$.

At F all the 180° reversals will have been completed ; and,

neglecting the relatively small contributions by 90° turns, the approximate total value of I will be given by the summation :

$$(AB + CD + EF) = I_s(1 + \sqrt{2} + \sqrt{3})/9 = 0.46\, I_s.$$

From the point F, in accordance with the temporary (but questionable) provisions of sections (8) and (9), it will be assumed that the 90° turns will be completed along FG, with FG parallel to OA. The point G will be fixed by the consideration that, with the 180° reversals and 90° turns all completed, the externally measured value of I at G should be :

$$\frac{I_s}{3}\left(1 + \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{3}}\right) = 0.76\, I_s,$$

so that the increment of I between F and G should be :

$$I_s\,(0.76 - 0.46) = 0.30\, I_s.$$

From G the magnetisation curve will proceed to saturation along GH, the equation of which can be calculated from knowledge of the anisotropy constants of the specimen.

(13) *Maximum Susceptibility (or Permeability)*.

The maximum susceptibility (or permeability) of a ferromagnetic is ordinarily defined as the value of the ratio I/H (or of the ratio B/H) at the point on the virgin magnetisation curve through which passes the tangent drawn from the origin.

Fig. 3 shows that, with the assumed distribution of crystal (and demagnetised domain) orientation, the point F will correspond to this tangent point, and that the physical significance of the point of maximum susceptibility is that it marks the completion of the 180° reversals. However, Fig. 3 also shows that this need not necessarily be the case, and that if, for example, the distribution of crystal orientation in the aggregate is such that the [100] crystal-group is predominant, then the point of maximum susceptibility may be expected to transfer its location to the point B, with a value of I now corresponding only to the completion of the 180° reversals in the [100] crystal-group (*see* section (25)). Similarly, if the [110] crystal-group predominates, the point of maximum susceptibility may be transferred to the point D (*see* section (27)).

These views of the physical significance of the point of maximum susceptibility, and of the factors which determine its location on the virgin magnetisation curve, appear to be novel, but it will be seen later that they may be of direct utility in practical magnetic analysis.

(14) *The Ideal Magnetisation Curve—Analysis*.

If the above synthesis of the ideal magnetisation curve of a polycrystalline aggregate is valid, then it follows that, given a

magnetisation curve of the type of Fig. 3, it should be possible, starting from the easily-fixed point of maximum susceptibility F, to use the curve to determine directly :

(a) The fundamental critical field strength $H_{0[100]}$ competent to initiate and propagate the 180° reversals with [100] conditions of magnetisation; and

(b) the distribution of crystal orientation or, more rigidly, the demagnetised distribution of domain orientation.

The experimental evidence to be described and discussed later appears to show that it is possible to contemplate just such a simple and direct method of analytical attack on the everyday magnetisation curves of commercial polycrystalline aggregates.

(15) *The Translational End-Point—Translational Saturation Intensity.*

Magnetisation effected either by 180° reversals or by 90° turns is often referred to as translational magnetisation, because both of these mechanisms involve a " translation of the boundaries between regions or a general shifting of the magnetic structure " [12] (*loc. cit.*, p. 184), as distinct from the rotational processes of approach to saturation, during which directional changes of regional magnetisation will occur without involving boundary changes. Adopting this definition, point G in Fig. 3 can be called the translational endpoint and the value of I at G can fittingly be termed the translational saturation intensity and be symbolised by I_t.

It will be clear that for a polycrystalline ferromagnetic the magnitude of the ratio I_t/I_s will depend solely on the distribution of crystal orientation; and that, for a body-centred cubic structure, it may vary between an upper limit of unity for 100% preferred [100] orientation, when I_t will correspond to the point C in curve I. of Fig. 2, and a lower limit of $(1/\sqrt{3})$ for 100% preferred [111] orientation, when I_t will correspond to the point B'' in curve III. of Fig. 2.

From this it follows that, given the virgin magnetisation curve II. of Fig. 2, it would be legitimate to deduce, simply from the observed location of the translational end-point C', that the curve represents a specimen with 100% preferred [110] orientation. That is, if I_s is known, the location of the translational end-point would provide an immediate indication of the general order of distribution of crystal orientation in an ideal polycrystalline aggregate.

PART V.—THE MAGNETISATION CURVE OF POLYCRYSTALLINE AGGREGATES—THEORY *VERSUS* OBSERVATION.

(16) *Initial Magnetisation.*

On the specific evidence at present available it is not possible to affirm—although the indirect evidence renders it highly probable —that the initial stage of the magnetisation process of a polycrystalline aggregate obeys the simple compounding law assumed in section (12). Furthermore, the special methods which Williams had to develop to obtain trustworthy measurements of the initial
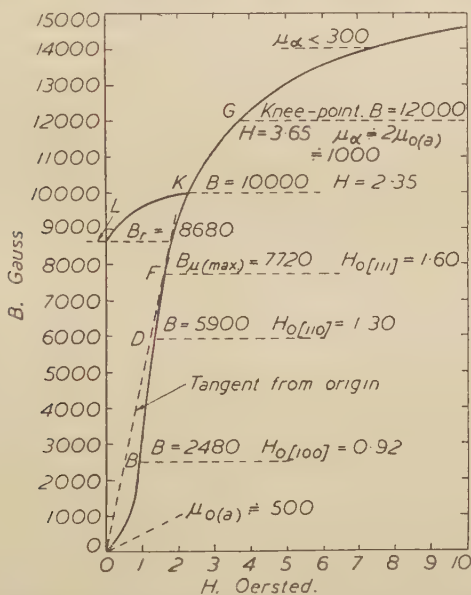
FIG. 4.—Technical Magnetisation Curve for Annealed Hot-Rolled Sheet.

permeability of single crystals would appear to indicate that there may be some difficulty in overcoming the experimental obstacles that impede direct verification of the assumption there made. Fortunately, the question is not of major practical importance, despite the fact that the actual characteristics of initial magnetisation will exert an appreciable influence on engineering magnitudes (*see* section (20)).

(17) 180° *Reversals—Qualitative.*

Fig. 4 reproduces the low-field range or steep part of what is now often called the technical magnetisation curve for a composite

" with and against " test-specimen of hot-rolled and annealed dynamo sheet steel, which is a low-impurity iron containing very little silicon.*

It will be noted that Fig. 4 represents a B/H curve. In discussing commercial material, B and μ will be used, in place of I and k, in deference to accepted practice; as Ewing pointed out, both usages have their own special virtues, and neither need be sacrificed to the other [18] (*loc. cit.*, p. iv).

Comparison of Fig. 4 with Fig. 3 shows that the outstanding discrepancy between theory and observation is the disappearance of the angularity of the ideal magnetisation curve. However, this ideal angularity owes its origin to nothing more than the over-simplification which results from assuming (*see* section (12)) that in each of the three idealised crystal-groups of a polycrystalline aggregate the 180° reversals of demagnetised domain magnetisation will be initiated and propagated at a unique value of the critical field strength for each crystal-group, thus giving the three vertical stages of Fig. 3. This assumption, however, can only be valid if the domain-boundary conditions across the 180° walls of the ferro-magnetic structure are uniform throughout the specimen; and, having regard to the probable physical factors which determine the origin and nature of the domain structure, it is next to impossible that this will ever be the case.

Let it be provisionally supposed that the point F ($H_{\mu(\max,)}$) in the technical curve of Fig. 4 corresponds to the point F ($H_{0[111]}$) in Fig. 3, and thus marks the completion of the 180° reversals. On this supposition it is evidently necessary to conclude that the smooth form of Fig. 4 originates from a spread of the critical field strengths over a range of values from not much above zero H up to $H_{\mu(\max,)}$. Such a spread can apparently only arise from non-uniformity, from point to point in the lattice structure, in the domain-boundary conditions across 180° walls. This non-uniformity in the distribution of domain-boundary imperfection will result in the 180° reversals being achieved not by the three large ideal steps AB, CD and EF of Fig. 3 but by a succession of much smaller Barkhausen jumps, all similar to those indicated on the section DF. The tips of all such little jumps will yield the smooth technical dotted curve $OBDF$. This picture of things is substantially nothing more than a domain theory paraphrase of Ewing's earlier conclusion, in connection with his brilliantly intuitive molecular theory, that " in no piece, except perhaps in a single crystal, could we expect to find that perfect regularity of structure which would be necessary to make the transition from one stage of the magnetising process to another quite sudden, and to give the curve the form of a series of sharp steps " [18] (*loc. cit.*, p. 312).

If this conception is valid, then the magnitude of $H_{\mu(\max,)}$

* Conventionally, if not quite accurately, the term " virgin " will in this paper be regarded as interchangeable with " technical."

for any given distribution of crystal orientation in a commercial polycrystalline aggregate will clearly depend on the spread intensity of domain-boundary imperfection; and it is reasonably certain that the lattice factors mainly responsible for this spread must be (a) residual plastic strain and (b) interstitial impurities. Very little, if any, plastic strain can be imagined as remaining in a well-annealed sheet product; so that the practical indication is that for 180° reversals the nature, quantity and distribution of interstitial impurities will constitute the chief determinant factors of domain-boundary conditions, and hence of the magnitude of $H_{\mu(\text{max.})}$ in commercial magnetic sheet material. It will be seen later that $H_{\mu(\text{max.})}$ must itself be one of the chief determinant factors of the measured coercive force (section (34)), so that the conclusion here reached is firmly supported by the large volume of painstaking experimental work which has been placed on record by Yensen and others. [22]

The harmful influence of interstitial impurities on the lattice conditions governing 180° reversals is also interestingly demonstrated by the phenomenon of magnetic ageing. This phenomenon is a specific effect of the general mechanism of precipitation-hardening, and the appreciable potential magnitude of what must almost inevitably be a domain-boundary effect has never been better revealed than by the very early observations of Roget,[23] *see also* Ewing [18] (*loc. cit.*, p. 193).

The direct and large influence of residual plastic strain on the lattice conditions for 180° reversals can readily be made evident by subjecting well-annealed sheet test-strips to a light tensile deformation. An elongation of the low order of $\frac{1}{4}\%$, which can reasonably be assumed to affect the domain boundaries only, will cause a substantial increase in the observed value of $H_{\mu(\text{max.})}$.

(18) 180° *Reversals—Quantitative. Trichotomy.*

$H_{\mu(\text{max.})} = 1.60$ in Fig. 4 will provisionally be assumed to represent the value $H_{0[111]}$ in Fig. 3 at which all the 180° reversals are completed. If this assumption is correct, then, according to the argument of section (17), $H = 1.60/\sqrt{3} = 0.92$ should represent the value $H_{0[100]}$ in Fig. 3, which will now become the value of H at which the 180° reversals of the [100] crystal-group are completed; and $H = 0.92\sqrt{2} = 1.30$ should represent the value $H_{0[110]}$ in Fig. 3, which will now become the value of H at which the 180° reversals are completed in the [110] crystal-group.

If these calculations are valid (and including for the moment the concurrent 90° turns of nibbling growth), the approximate contributions made to the observed $B_{\mu(\text{max.})} = 7720$ by each of the simulated crystal-groups in the polycrystalline aggregate should be as shown in Table I.

If the demagnetised distribution of the directions of domain

magnetisation is equal along each of the six possible [100] crystal directions, the further values shown in Table II. can be deduced from the last column of Table I.

TABLE I.—*Crystal-Group Contributions to* $B_{\mu\,(max.)}$—*Fig.* 4.

Simulated Crystal-Group.	Contribution to $B_{\mu\,(max.)}$.	
	As B. Gauss.	As % of $B_{\mu\,(max.)}$.
[100]	2480	32·1
[110]	3420	44·3
[111]	1820	23·6
...	7720	100·0

The values thus arrived at in the fourth column of Table II. are seen to be of significantly similar order to those derived from the analysis of saturation-torque curves for sheet material of the same basic type.[5]   In computing the torque results shown in the last column of Table II. it has been assumed that for the present

TABLE II.—*Estimated Distribution of Crystal Orientation*—*Fig.* 4.

Crystal-Group.	Contribution to 180° Reversals as % of $B_{\mu\,(max.)}$ (Table I.).	Estimated Simulated Distribution of Crystal Orientation.		
		From Fig. 4.		From Typical Torque Analyses. %
		Proportionate.	%.	
[100]	32·1	32·1/1·00 = 32·1	41·6	36·7
[110]	44·3	44·3/$\sqrt{2}$ = 31·4	40·7	44·0
[111]	23·6	23·6/$\sqrt{3}$ = 13·6	17·7	19·3

approximation it is permissible to say that where the torque-analysis estimates indicate a proportion of random orientation, this proportion can be regarded as equally distributable over the three ideal crystal-groups.

Fig. 4 is not a " hand-picked " curve for the immediate purpose. It was first published in 1931 as part of a series exhibiting the average performance of different commercial grades of dynamo and transformer sheet material.   During the present investigation, however, a large number of similar routine magnetisation curves have been analysed in similar fashion ; and it has been found that they consistently reproduce the same informative threefold division of the steep part of the curve, to which it seems not inappropriate to apply the term " trichotomy."

Even if existing conditions did not prohibit the presentation of a large volume of detailed experimental evidence, it would go beyond

the intended scope of the present survey to discuss any but the broadest aspects of this new outlook on the probable physical significance of the steep part of the technical magnetisation curve.* It can, however, be stated with reasonable confidence that this method of trichotometric analysis is very usefully sensitive, not only to the variations in the distribution of crystal orientation that are to be expected along different sheet directions relative to the rolling direction, but also to the structural changes which occur at various stages of hot-rolling and heat treatment, and to the structural variations which may be expected to result from relatively minor differences in rolling and heat-treating conditions.

It has also been observed that in practically all composite technical magnetisation curves of the material-type of Fig. 4, the middle [110] section BD is virtually straight as shown, with two points of inflection markedly occurring at or very near to the ideal values of $H_{0[100]}$ and $H_{0[110]}$ as calculated from the easily fixed point of maximum permeability, which theoretically corresponds to the ideal value of $H_{0[111]}$ in Fig. 3. (The conception of trichotomy originated, in fact, from noting that in the magnetisation curves for commercial sheet test-samples the H-limits of the middle straight section of the steep part so consistently approximated to the ideal H_0 ratios.)

Furthermore, in cases where freak curves are recorded which exhibit a radical departure from normal trichotomy, or in which habitually smooth inflectional features are replaced by more sharply localised changes of curvature justifiably described as kinks, it is usually found easy to account for such abnormalities by reference to known variations in rolling and heat-treating conditions which would be expected to produce structural differences of the type predictable by the application of the principles here outlined. An illustrative case of especially interesting deviation from normal trichotomy is discussed in section (25).

Since the principles of the trichotometric method would appear to be readily applicable in many cases where X-ray, torque-magneto-meter and optical etch-pit methods of orientation analysis may all be difficult or impracticable, it has been considered permissible to make this brief reference to exploratory observations which may be of interest and use to investigators in other fields also concerned with ferromagnetic material.

(19) *Deficiency in* 180° *Reversals.*

Although a simple deduction from the domain theory thus appears to be perhaps unexpectedly successful in dissecting the

* Moreover, there would in any case be but little justification for the multiplication of curves and Tables, since a large volume of cognate experimental material is constantly available in many laboratories equipped with the simple apparatus required for the easy and speedy reproduction of the type of result upon which the present treatment is based.

steep part of the technical magnetisation curve for hot-rolled sheet material, Table II., whilst exhibiting this apparent success, reveals at the same time a second discrepancy between theory and observation.

Table II. yields a trichotometric estimate of the simulated distribution of crystal orientation in the specimen covered by Fig. 4 which is in satisfactory agreement with the approximate values indicated by other methods.   Table III. uses this estimate to calculate the theoretical value of B_π, which will here be used to symbolise the total potential contribution by 180° reversals to the externally measured magnetic induction B.   In Table III. it has been assumed that, for the specimen of Fig. 4, $(B - H)_s = 21500$ Gauss, and that the demagnetised directions of domain magnetisation are equipartitioned along the six possible [100] crystal directions.

TABLE III.—*Theoretical Crystal-Group Contributions to* B_π—*Fig.* 4.

Crystal-Group.	Simulated Distribution of Crystal Orientation (Table II). %.	Theoretical Crystal-Group Contribution to B_π. Gauss.
[100]	41·6	$21500 \times 0·416 \times 1/3 \quad = 2980$
[110]	40·7	$21500 \times 0·407 \times \sqrt{2}/3 = 4125$
[111]	17·7	$21500 \times 0·177 \times 1/\sqrt{3} = 2200$
...	100·0	Theoretical $B_\pi = 9305$

Table III. thus gives a theoretical value of $B_\pi = 9305$, whereas Table I. shows that, even including the contributions made by the 90° turns of assumed concurrent nibbling growth, the observed value, which will be symbolised as $B_\pi{}'$, is no more than 7720.

The most likely and reasonable explanation of this discrepancy seems to be indicated by the following argument :

(1) For any given distribution of crystal orientation (or, more rigidly, of demagnetised domain orientation) a deficiency in the observed value of $B_\pi{}'$ can result only from a deficiency in the proportion of the lattice which contributes to the 180° reversals.

(2) Such a deficiency in the operative proportion of the lattice can result only from a decrease in its effective content of homogeneous domains as defined in section (3).

(3) Such a quantitative deficiency in lattice homogeneity must be caused by an increase in the proportion of those regions of the lattice in which the regular atomic spatial arrangement is seriously modified.

(4) Such regions of space-lattice disorder will be represented in a finite polycrystalline aggregate (*a*) by the domain boundaries, (*b*) by the crystal boundaries and (*c*) by the external surfaces.

This argument clearly leads to the conclusion that if in well-annealed sheet material of given composition and thickness the domain-boundary conditions are largely determined—as section (17) indicates is probable—by the content of interstitial impurities, then the magnitude of the translational deficiency $(B_\pi - B_\pi')$ should increase as the grain size decreases. The experimental data as yet available are inadequate for the direct verification of this deduction; but if the argument is valid, the general effect of decreasing grain size, other things being equal, should be to increase the proportion of " secondary " $180°$ reversals left over at B_π' to be coerced at higher values of H than should ideally be required; and it will be seen later (section (33)) that such a result must involve an increase in the hysteresis energy loss per cycle of alternating magnetisation.

It therefore follows that this predicted increase in the hysteresis loss with decreasing grain-size should be closely related to the proportionate volume of the lattice affected by the disturbed conditions at crystal boundaries; and Yensen's work, in addition to demonstrating the very harmful effect on magnetic properties of fantastically small percentages of interstitial impurities, has very clearly shown that this is undoubtedly the case.[22] The general interpretation of the evidence relating to the influence of grain size on the hysteresis loss has been discussed by the present author in a previous communication.[24]

There would appear, however, to be no sound reason for believing that, from the demagnetised state up to the completion of the " primary " $180°$ reversals at B_π', the existence of serious lattice imperfections at the major structural boundaries (including the external surface) will affect the quantitative distribution of the primary reversals between the idealised crystal-groups of a polycrystalline aggregate. That is, the harmful effects of crystal boundaries and of external surfaces will not be expected to disturb the normal trichotomy of the technical magnetisation curve. This view is supported by the experimental observation that, although a light tensile elongation of the low order of $\frac{1}{4}\%$ very markedly decreases the value of $B_{\mu(\text{max.})}$ in a well-annealed sheet sample, the trichotometric estimate of the distribution of crystal orientation remains virtually unchanged.

It therefore seems legitimate to conclude that the translational deficiency in primary $180°$ reversals, when coupled with the observed value of H_π' (or with the value of $H_{\mu(\text{max.})}$, as the case may be), can be regarded as providing a usefully simple and direct indication of the general intensity of lattice imperfections. Such imperfections will clearly include those attributable to impurities normally located at crystal boundaries as well as the adverse effect of the boundaries themselves, the quantitative incidence of which per unit of volume of the lattice will itself be affected by the general impurity content.

(20) *Completion of* 180° *Reversals.*

The point F in Fig. 3 corresponds to $H_{0[111]}$; and if all the 180° reversals are completed at that point, the ideal magnetisation curve will proceed along FG, which has hitherto been assumed to run parallel to the initial slope OA, the magnitude of which will be symbolised as $\mu_{0(a)}$. In practice, however, the existence of a translational deficiency at H_π' will be expected to cause the slope of that portion of the technical curve which immediately succeeds H_π' to be appreciably greater than that indicated by the estimated value of $\mu_{0(a)}$. This follows from the apparently reasonable assumption that, although the secondary 180° reversals will be harder to initiate and propagate than the primary contingent, they should for the most part tend to be achieved with values of dB/dH much more akin to the general primary 180°-reversal slope than to the initial 90°-turn slope.

The general form of the technical curve for well-annealed material suggests, in fact, that it is not very wide of the mark to regard the majority of the secondary 180° reversals as being completed, concurrently with the continued operation of the mechanism of 90° turns, over that region of the curve which lies between B_π' and the point at which the curve registers a local value of dB/dH of the order estimated as being appropriate, after the 180° reversals have been completed, for 90° turns only. Fundamental considerations exist, however, which preclude the retention of the simplifying assumption that in Fig. 3 the parallelism of FG with OA will truly represent the magnitude of dB/dH after the 180° reversals have been largely dealt with (*see* sections (8) and (9)).

In Fig. 1, for magnetisation along the [100] crystal direction CA, the lattice capacity for " stimulating " the mechanism of 90° turns will clearly be substantially increased when all anti-parallel domains such as domain No. 3 have been brought into vectorial parallelism with favoured domains such as domain No. 2, because both sets of domains, which by hypothesis must be of equal total volume, will then be equally competent to stimulate nibbling growth ; and since the magnitude of the stimulus to nibbling growth must be dependent on the internal surface area associated with directionally-favoured domains, it does not seem unreasonable to argue that when the bulk of the 180° reversals have been completed the stimulating internal surface area will have been nearly doubled, and that the local magnitude of dB/dH, for 90° turns only, should then be of the order of $2\mu_{0(a)}$. (In what follows, the symbol $\mu_{\pi/2}$ will be used to denote the differential permeability for 90° turns only.)

Precision measurements of $\mu_{0(a)}$ are difficult, and are certainly not to be expected from routine methods, but an enlargement of the early portion of Fig. 4, supported by derived curves, indicates that the initial linear slope simulates a value of $\mu_{0(a)}$ of the order of 500. This means that the greater part of the 180° reversals should

be completed when the local slope of Fig. 4 gives $\mu_d \fallingdotseq 1000$, which occurs with $B = 12000$ at point G.

The latter value of B is seen to be considerably in excess of the computed value of $B_\pi = 9305$ shown in Table III.; but during the whole process of magnetisation from O to G there will have been an appreciable B-contribution by $90°$ turns. The approximate magnitude of this contribution can now be assessed by assuming that $\mu_{\pi/2}$ will increase in roughly linear fashion from an initial value of 500 to its estimated final value of 1000 at G, thus giving a mean value of the order of 750 over the range O to G. At G the value of H is $3·65$, whence the estimated contribution by $90°$ turns to B at G will be $750 \times 3·65 = 2740$. This yields an experimentally estimated value of B_π of the order of $(12000 - 2740) = 9260$, against the theoretical value of $B_\pi = 9305$ arrived at by Table III. The order of agreement between theory and observation is again seen to be encouraging; and the result recorded appears to be typical of the general run of observations made on commercial hot-rolled magnetic sheet steel of all grades.

(21) *The Knee of the Technical Magnetisation Curve.*

The term knee as applied to the technical magnetisation curve is a familiar one, although no attempt seems hitherto to have been made to define it; but by reference to the typical curve of Fig. 4, and to the treatment here outlined, it is suggested that the knee of the technical curve can be regarded as that region of the curve which lies between $B_{\mu\,\text{(max.)}}$ and the point on the curve at which the $180°$ reversals—both primary and secondary—should normally be largely completed, the latter "knee-point" being approximately located by the condition that $\mu_d = 2\mu_{0\,(a)}$. Thus the knee of the curve in Fig. 4 will be the section FG.

In general, therefore, the knee of the technical magnetisation curve will be the region which records the approximate completion of the $180°$ reversals which remain to be accomplished at $B_{\mu\,\text{(max.)}}$; and the value of B at the knee-point G (Fig. 4), which can be conveniently symbolised as B_k, should be of the same order as the sum of B_π and the estimated B-contribution by $90°$ turns from the demagnetised state up to B_k.

(22) *The Nature and Origin of Secondary Reversals.*

It would appear to be inescapable that the observed trichotomy of the steep part of the technical magnetisation curve must connote some fundamental and sharp physical difference between the lattice conditions associated respectively with primary and secondary $180°$ reversals. If the difference were merely one of smooth degree in some potentially determinant factor, such as the intensity of domain-boundary imperfection or variation in domain size, it would be difficult to imagine any other major effect on the magnitudes of

the virgin curve beyond an increase in the spread of the critical field strength. This would simply mean that the ideal trichotomy would be exhibited up to some higher value of $H_{\mu\,(\text{max.})}$, at which all (or at any rate the bulk) of the 180° reversals would be completed; any substantial translational deficiency at such an increased value of $H_{\mu\,(\text{max.})}$ would thus be inconceivable, and the apparent necessity for distinguishing between primary and secondary reversals would vanish.

The proportion of secondary reversals is known to increase rapidly with any worsening of domain-boundary conditions arising either from an increase in the content of interstitial impurities or from an increase in the amount of residual plastic strain, both of which factors may conceivably locally influence the domain size; and the grain-size effect suggests that the internal macrostructure may disturb the microstructure more profoundly than by merely varying the lattice content of grain-boundary "disregistry." However, the observed behaviour of secondary reversals exhibits none of the normal directional characteristics of crystal-groups which appear to be responsible for the trichotomy of the steep part of the magnetisation curve. All the evidence therefore tends to the conception that secondary reversals are most likely to be associated with some measure of abnormal and apparently random fragmentation of the domain structure, which locally decreases, as argued in section (19), the proportion of homogeneous domains in those regions of the lattice affected by interstitial impurities, plastic strain or major structural boundaries (including the external surface). This conception of localised domain fragmentation is not novel in so far as it involves the associated ideas of internal stress-concentrations and variations in the relative thickness of domain-boundary walls; but the subject is one which has hitherto been given little but academic attention.[16] From the practical standpoint, however, the problem is of considerable importance, since the incidence of secondary reversals will directly affect :

(a) The location of the knee-point of the virgin magnetisation curve (section (21)), and hence also the high-induction permeability; and

(b) the observed magnitude of the alternating hysteresis loss (see section (33)).

The conception here outlined would clearly support the conclusion arrived at in section (19) that the trichotometric estimate of the magnitudes associated with the translational deficiency in primary 180° reversals should afford a direct indication of the general intensity of lattice imperfections.

(23) Completion of 90° Turns.

When the 180° reversals and the 90° turns have all been accomplished, the processes of translational magnetisation (section (15))

will be complete; and the translational saturation value of $(B - H)$, which can be symbolised as B_t, should be calculable for Fig. 4 as shown in Table IV., using Table II., and putting $(B - H)_s = 21500$ gauss.

The simple theory would predict that between $B_k = 12000$ and $B_t = 17330$ the slope of the magnetisation curve should be not less than the value given by $\mu_d = 2\mu_{0(a)}$; and Fig. 4 again reveals a discrepancy between theory and observation. It is seen, in fact, that as soon as the knee-point G is passed the value of μ_d begins to decrease so rapidly that even at $B = 14000$ it has already been reduced to less than 300, as compared with its approximate value of 1000 with $B_k = 12000$.

TABLE IV.—*Crystal-Group Contributions to* B_t—*Fig.* 4.

Crystal-Group.	Simulated Distribution of Crystal Orientation (Table II.). %.	Estimated Contribution to B_t at Completion of 180° Reversals and 90° Turns. Gauss.
[100]	41·6	$21500 \times 0\cdot416/1\cdot00 = $ 8940
[110]	40·7	$21500 \times 0\cdot407/\sqrt{2} = $ 6190
[111]	17·7	$21500 \times 0\cdot177/\sqrt{3} = $ 2200
...	100·0	Total $B_t = $ 17330

This discrepancy appears to be reasonably explained by the consideration that beyond the knee-point the influence of rotational processes on the partially completed translational magnetisation of the [110] and [111] crystal-groups must increasingly tend to produce lattice conditions adverse to the normal completion of outstanding 90° turns; and the magnetisation curves of similarly-processed magnetic sheet steel consistently reveal this marked " deadening " effect very soon after passing the knee-point as defined in section (21), thus conducing to the observed rapid tendency above that point to a parallelism which is essentially a characteristic of the rotational mechanism of magnetisation (*see* section (7) (*d*)).

The retarding effect of rotational processes should theoretically come into incipient operation in the later stages of the steep region, and may conceivably cause the value of B_k as approximately located in section (21) to be a little too low; but, owing to the pronounced flattening of the curve in the vicinity of B_k, it is not to be expected that this possibility will seriously disturb the final result of calculations of the type made in section (20).

Direct evidence of the rapidly increasing influence of rotational processes from the knee-point onwards is furnished by measurements of magnetostrictive dimensional changes.[7]

(24) *Approach to Saturation*.

For iron and iron-silicon alloys with similar elastic constants and substantially similar distribution of crystal orientation between the [110] and [111] crystal-groups there is little of present interest in the parallelism of their technical magnetisation curves above B_t, except in so far as the general level of B/H curves with respect to the B-axis can usefully indicate differences in, and the approximate magnitude of, saturation values; or, conversely, if the saturation value is known, the approximate content of the [100] crystal-group in a polycrystalline aggregate can be assessed by applying the principles of section (15).

(25) *Deviation from Normal Trichotomy*.

An interesting example of deviation from the normal trichotomy of the polycrystalline magnetisation curve is furnished by curve (a) of Fig. 5, which refers to an annealed specimen of 3% iron-silicon alloy cold-reduced strip magnetised parallel to the rolling direction.

If $B_{\mu (\text{max.})} = 4750$ (curve (a)) is made the starting-point for an estimate of the distribution of crystal orientation according to the method of section (18), absurd results will be obtained for a material in which the conditions of rolling and heat treatment are known to produce a marked degree of preferred [100] orientation about the rolling direction.   It is therefore necessary to conclude that in this case, as foreshadowed in section (13), $B_{\mu (\text{max.})}$ corresponds

TABLE V.—*Estimated Distribution of Crystal Orientation—*
Fig. 5, Curve (a).

Crystal-Group.	H_0. Oersted.	Crystal-Group Contribution to B_{π}'.		Estimated Simulated Distribution of Crystal Orientation. %.	
		As B. Gauss.	As % of B_{π}'.	By Trichotomy.	By Torque Analysis.
[100]	0·265	4750	66·9	75·2	72·2
[110]	0·375	1500	21·1	16·9	13·9
[111]	0·459	850	12·0	7·9	13·9

to the point B in Fig. 3 instead of to the normal point F.   On this adjusted basis the results shown in Table V. are obtained.

Having regard to the simple nature of the basic theory used and to the assumptions made concerning the interpretation of torque-analysis estimates, Table V. appears to exhibit further evidence of satisfactory agreement between prediction and observation.

It is to be remembered, however, when comparing trichotometric estimates with those derived from observations of saturation-

torque that the experimental conditions differ profoundly and that it is by no means certain that the relative magnitudes of response by the three simulated crystal-groups ought to be identical in the two cases. Moreover, torque-analysis estimates of the distribution of crystal orientation sometimes differ from those arrived at by other recognised methods; and different observers may record different quantitative interpretations of similar saturation-torque curves.[25] Further, in " fitting " torque curves even the same observer can generally find a choice of solutions. In any event, neither method can yield more than an estimate. It is only the general order of agreement that can be in any way significant.

It is also necessary to bear in mind that for annealed sheet material it is known that the actual orientation of the ideal crystal-groups may be more or less tilted or twisted with respect both to the rolling direction and to the rolling plane; and this will clearly tend to cause a departure of the observed H-ratios from their theoretical relationship, especially when the test-strips are all cut along one direction. Composite " with " and " against " test-specimens of such material undoubtedly mask many directional idiosyncrasies (see section (27)); and, as is well evidenced by Fig. 4, the observed effects of this masking can have their own inherent and informative significance. It will be clear, however, that the trichotometric method of analysis should always be applied by reference to its underlying principles rather than to bare ideal arithmetic (see also section (26)).

(26) *Preferred Domain Orientation.*

As a non-essential simplification (see section (4)) it has hitherto been assumed that in the demagnetised state there exists an equi-partition of the directions of domain magnetisation along the six possible [100] cubic crystal directions; but it is quite possible to record evidence of preferred domain orientation superimposed upon preferred crystal orientation.[7] In such cases the application of trichotometric principles will enable the degree of preferred domain orientation to be approximately assessed.

The virgin magnetisation curve may therefore be directly useful in the study of the processes of plastic deformation and recrystallisation, since it is now accepted that the phenomena not only of ferromagnetism but also of the working and annealing of metals must ultimately depend on the disposition and behaviour of the underlying secondary structure of the crystalline state of matter. Measurements of saturation-torque have already been proposed as an aid in this connection; [26] but the virgin magnetisation curve may possibly provide a simpler and more efficient tool, since it appears to be competent to probe a little more deeply into the basic lattice structure.

The existence of preferred domain orientation will inevitably affect the magnitudes recorded by directional measurements of

magnetostrictive dimensional changes (*see* section (5)). This question has been discussed by Brailsford and Martindale.[7]

Further, since the quantitative trichotomy of the steep part of the virgin curve will be determined by the demagnetised distribution of domain orientation, uncorrected trichotometric estimates of lattice orientation will be expected to differ from those arrived at by the more familiar methods if the domain orientation does not run substantially parallel with the grain orientation.

(27) *Significance of Directional Variations*

A potentially important experimental fact is that when test-samples cut from the same annealed sheet are magnetised along different directions with respect to the rolling direction the observed values of H_0 for the three ideal crystal-groups may, under certain conditions, vary both absolutely and relatively with the direction of magnetisation. In hot-rolled sheets the effect is rarely of outstanding magnitude, and so far as the H_0 ratios are concerned seems usually to be absent; it can, however, be very marked in cold-reduced strip, as shown in curve *b* of Fig. 5, which refers to the same material as curve *a*, but with the magnetisation now at right angles to the direction of rolling.

Curve *b* shows that even if the recorded value of $B_{\mu\,(\text{max.})} = 3750$ is now associated, as is most likely, not with the terminal value of $H_{0[100]}$ but with the terminal value of $H_{0[110]}$, the latter value in curve *b* is far in excess of its rolling-direction value as deduced from curve *a*.

FIG. 5.—Technical Magnetisation Curves for Annealed Cold-Reduced Strip.

Curve *b* strongly suggests, however, that for the diminished content of [100] orientation which now presents itself to transverse magnetisation the value of $H_{0[100]}$ remains virtually unchanged. In this connection it is to be noted that in Table V. the estimated percentage of the [100] crystal-group will almost certainly comprise two very different types of [100] orientation.[5, 25] The predominant type will be associated with (110) planes parallel to the rolling

plane * and will thus constitute the major component of the [110] crystal-group for transverse magnetisation; but there will also be a small crystal-group with all its [100] directions set more or less parallel with or at right angles to the rolling direction, and under transverse magnetisation this small contingent appears to retain very much the same critical field strength $H_{0[100]}$ as deduced from curve a of Fig. 5.

If it is assumed that in curve b the observed anomaly in [110] magnetisation will not materially affect the normal H_0-ratio of $\sqrt{3}/\sqrt{2}$ as between the [111] and [110] crystal-groups, the direct application of trichotometric principles will indicate that the simulated crystal-group contributions to primary 180° reversals should be delimited by the observed point of inflection B, the observed $\mu_{(max.)}$ point D and the calculated point F. On this basis it is possible to establish the results of Table VI., which, in conjunction with Table V., appears to be reasonably confirmatory of the broad validity of a very simple working hypothesis.†

TABLE VI.—*Estimated Distribution of Crystal Orientation—Fig. 5, Curve* (b).

Crystal-Group.	H_0. Oersted.	Crystal-Group Contribution to B. Gauss.	Estimated Simulated Distribution of Crystal Orientation. %.	
			By Trichotomy.	By Torque Analysis.
[100]	0·30	550	17·0	17·7
[110]	1·05	3200	69·8	68·4
[111]	1·29	750	13·2	13·9

These observations can apparently be interpreted only as indicating that, under certain conditions, the intensity of lattice imperfection across the 180° walls between anti-parallel domains may itself exhibit directional variations with respect to the rolling direction; that is, if CA in Fig. 1 is the rolling direction, the critical field strength applied parallel to CA which will break down the 180° wall between domains Nos. 2 and 3 may be very different from the critical field strength applied parallel to BA which will break down the 180° wall between domains Nos. 1 and 4.

Such an interpretation seems to force the conclusion that

* This means that on transverse planes perpendicular to the rolling plane the cube edges will all be at 45° to the rolling plane, thus making the direction of transverse magnetisation parallel to the [110] directions of cube face diagonals.

† It is perhaps even tempting to regard Tables II., V. and VI. as collectively providing a case in which "the probabilities against the agreement being a mere coincidence are so overwhelming that the physicist feels justified in disregarding this possibility." [27]

variations in the prior conditions of plastic deformation and heat treatment can lead to one or more of the following results :

(*a*) Varying degrees of selective segregation of interstitial impurities ;

(*b*) the association of the final distribution of lattice orientation with directional differences in the magnitude, and (in some cases) apparently also in the sign, of residual elastic distortion arising from the internal dimensional adjustments inseparable from the initial acquisition of the " unnatural " demagnetised state ; * and

(*c*) directionally-operative variations in domain shape, about the precise nature and effects of which too little is yet known but which may not inconceivably be associated with either (*a*) or (*b*).

Further investigation of these as yet obscure directional effects may go far to account for some of the abnormalities of single-crystal observations, which may be attributable to peculiarities in lattice conditions originating during the processes of primary solidification. Fig. 5 shows that, in spite of the profoundly different nature of the two types of material, the commercial order of divergence between theory and observation seems to be broadly similar to that recorded by single-crystal measurements.[4, 21] The ultimate solution of the single-crystal problem may therefore have considerable practical significance.

(28) *The Polycrystalline Magnetisation Curve—Working Model.*

The preceding treatment of the process of virgin magnetisation of polycrystalline iron (or iron-silicon alloy) can be conveniently summarised for commercial annealed sheet aggregates by the working model of Fig. 6, which is largely self-explanatory.

Curves 1 and 2, for which a similar distribution of crystal orientation has been assumed, indicate that a high silicon content will increase the initial slope OA and lower the value of $H_{k\,(\text{max.})}$ at B, but that it will at the same time reduce the saturation intensity I_s, and hence also the knee-point value of I_k at K and the translational end-point value of I_t at T. These joint effects account for the familiar and unwelcome intersection of comparable technical curves at some such point as X.

Curve 3 exhibits the characteristics of a high degree of preferred [100] orientation coupled with a high silicon content. In relation to curve 2 the initial slope is further improved † and the value of

* This conception follows directly from the known effects of elastic deformation on ferromagnetic behaviour. Stated differently, the factors involved will be those governing the disorder-order transformations which occur during final cooling from the Curie point.

† Consideration of Fig. 1 and equation (1) will show that this may not be true if there also exists a high degree of parallel preferred domain orientation, which will statistically involve a substantial reduction in the internal

$H_{k\,\text{(max.)}}$ at B is again lowered; but in this case the value of I_t at T will be increased (section (15)).

In all three curves the location of the maximum-susceptibility point B with respect to the I-axis will depend on the demagnetised distribution of domain orientation (section (26)).*

The sections KMT of the curves have been drawn to indicate that the completion of the 90° turns is expected to commence, along KM, with $dI/dH = 2k_{0(a)}$; but that, according to the actual distribution of lattice orientation, there will be a more or less rapid
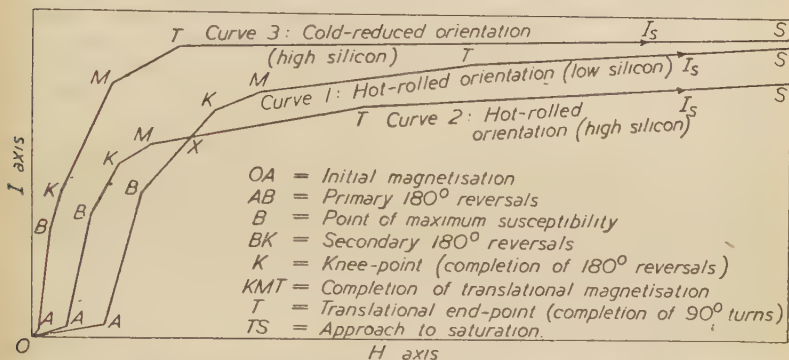
FIG. 6.—Polycrystalline Magnetisation Curve for Annealed Sheet Aggregates; working model.

tendency for the curves to attain the slope of the final stage of approach to saturation along TS (section (23)).

The trichotometric estimates of Tables II. and V., coupled with sections (9) and (10), would indicate that the relative distribution of crystal orientation as between the [110] and [111] crystal-groups should result in the " approach slope " TS of curve 3 (cold-reduced silicon strip) being inferior to that of curve 2 (hot-rolled silicon sheet)—an effect which is generally quite marked.

surface area, per unit of lattice volume, across which nibbling growth can occur (*see* section (20)). In the extreme case, with 100% preferred crystal orientation along a direction of easiest magnetisation, accompanied by 100% of parallel preferred domain orientation, the magnetisation curve for the preferred direction would be expected to be coincident with the H-axis until H attains the critical field strength for the initiation and propagation of 180° reversals. Transverse to this preferred direction, magnetisation would be next to impossible. Such a case appears to be well exemplified by the classical behaviour of pyrrhotite [20] (*loc. cit.*, p. 152).

* A study of Fig. 6 will show that if from any cause there is an abnormally low I-contribution by primary reversals, the consequent reduction in the length of the sections AB will tend to transfer the $k_{\text{(max.)}}$ point B to the knee-point K. For reasons that are still obscure (*see* section (27)), some effect of this kind appears to be revealed by the anomalies recorded by Williams on his iron-silicon single crystal along the [110] and [111] directions. [4]

PART VI.—CYCLIC MAGNETISATION AND THE HYSTERESIS EFFECT

(29) *Reversible and Irreversible Magnetisation.*

If from any point along the initial stage OA in Fig. 3, the value of H is reduced to zero, the ideal magnetisation curve will retrace its path along the reverse direction AO and regain a zero value of I when H again becomes zero. Similarly, if from any point along the final rotational stage GH the value of H is reduced to its value at G, the curve will retrace its path along the reverse direction HG and regain at G the value of I measured at that point during ascending magnetisation. Both the initial and the final stages of the magnetisation process will thus exhibit elastic characteristics; and this type of magnetisation can therefore appropriately be termed reversible.

If, however, the ascending value of H is reduced at any point such as K, intermediate between A and G, the curve will not retrace its ascending path along KF, but will follow a new path such as KL, thus causing the value of I corresponding to any given descending value of H to be greater than the value of I recorded at the same ascending value of H. Behaviour of this kind is always associated with the translational processes of magnetisation, which are partially irreversible.

(30) *Hysteresis and Coercive Force.*

The lagging behind of descending magnetisation described in section (29) and for which Ewing coined the term hysteresis, is primarily due to the fact that $180°$ reversals of the directions of domain magnetisation can only be revoked by the application of a coercive value of H of equal magnitude but of opposite sign to the field strength at which they were originally achieved. This will mean that, apart from the reversible effects of rotational processes, no further change can occur in the vectorial magnetisation of any given reversed domain except through the application of this coercive value of H, which will be the coercive force for that domain.

The coercive force for any given reversed domain will thus be determined by the critical field strength required to initiate and propagate its $180°$ reversals during virgin magnetisation; and a simple (if slightly unorthodox) way of dealing analytically with its controlling factors is to consider that in the transition regions between initially anti-parallel domains there will exist conditions to which equation (1) is broadly applicable. From this standpoint, if I_c is the value of I corresponding to the critical field strength or coercive force H_c, the following relationship will result :

$$I_c/H_c = k_0 = aI_s{}^2/\lambda_0 Z_i \quad . \quad . \quad . \quad . \quad . \quad (6)$$

whence

$$H_c = (I_c/I_s)(\lambda_0 Z_i/aI_s) \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Putting $(I_c/I_s) = p_c$ equation (7) becomes :

$$H_c = p_c(\lambda_0 Z_i/aI_s) = p_c I_s/k_0 . \qquad . \qquad . \qquad . \qquad . \qquad . \qquad (8)$$

where the numerical factor p_c can be directly related, by definition, to the fractional volume of the lattice in which nibbling growth has to proceed before a local breach can be effected in the 180° wall (*see* section (7) (*b*)). Its more orthodox definition associates it with " the ratio between the thickness of the wall and the wave-length of the internal stresses." [16]

Equations (6) and (8) show that, other things being equal, the initial susceptibility k_0 will depend solely on the magnitude of Z_i, whereas the coercive force H_c will depend in addition on the distribution of the lattice disturbances. The value of p_c will be small " if the disturbances are highly localised or very smooth " ; [16] its maximum value will obviously be unity.

It has already been noted in section (7) (*b*) that the experimental evidence indicates that the initiation and propagation of 180° reversals is essentially a nucleation process. It is also well known that in Fig. 2 the location of the points A, A' and A'' will determine the areas of the work triangles (based on the I-axis) which give a measure of the external energy involved, per unit of volume, in arriving at those points from the demagnetised state. Therefore, if the view is taken that the critical field strength or coercive force H_c registers the completion of the work that must precede nucleation, it is easily seen that the established relationships of equation (4) would follow directly from the ideal proposition that for an isotropic distribution of domain-boundary conditions the pre-nucleation work per unit of volume should be a lattice constant independent of the directional conditions of magnetisation. Williams' experimental results [4] show quite clearly, however, that the relationships of equation (4) may hold even if this derived proposition is not applicable. Provided, therefore, that the directional effective strength of any given external magnetising field is correctly assessable by reference to the normal crystallographic considerations of section (9), the inference apparently must be that the quantity p_c in equation (8) is a lattice magnitude which can vary directionally, for reasons that are not yet clear, even in a single crystal (*see also* section (27)).

(31) *Residual Magnetisation.*

From sections (29) and (30) it follows that if H is simply reduced to zero from any value exceeding the coercive force for any given domain, that domain must inevitably exhibit a residual intensity of externally measurable magnetisation the magnitude of which will be a joint function of the saturation intensity I_s and of the angular deviation between the demagnetised direction of domain magnetisation and the direction of application of H ; and in any given ferromagnetic specimen, whether single-crystal or polycrystalline, the

sum of all such domain-elements of residual magnetisation will constitute the externally measurable residual intensity usually symbolised as I_r (or the equivalent residual induction usually symbolised as B_r).

Although residual magnetisation is always associated with irreversible translational processes, not all translational processes are irreversible. For example, for the representative technical curve of Fig. 4, starting from the point K at $B_{\mathrm{max.}} = 10000$, measurements of reversed magnetisation gave typical B/H values as indicated by KL, with $B_r = 8680$. Using the method advanced in section (20) for the estimation of $\mu_{\pi/2}$, its mean value over the virgin magnetisation range O to K should be of the order of 700. With H at $K = 2 \cdot 35$, this will yield an estimated 90°-turn contribution to B from O to K of the order of $(700 \times 2 \cdot 35) = 1645$; and since $(B_{\mathrm{max.}} - B_r) = (10000 - 8680) = 1320$, it is clear that, accepting the irreversibility of 180° reversals (until H becomes sufficiently negative), a large proportion of the 90° turns contributory to $B_{\mathrm{max.}}$ must be reversible. This conclusion is supported by Ewing's general data on residual intensity [18] (loc. cit., p. 316).

Ewing's observations go further. They show that the rate of increase of I_r with increase in the peak value of H (for reversed magnetisation) is high for peak values of H associated with the primary 180° reversals over the steep part of the virgin curve, but that it falls away rapidly over the region of the knee, with the result that I_r increases but little beyond a peak value of H closely corresponding to its virgin value at the knee-point. From this it follows that :

> (a) The knee-point does mark the bulk completion of 180° reversals (see section (21)); and
> (b) 90° turns occurring above the knee-point must tend to be wholly reversible.*

It has been observed that the ratio $I_r/I_{\mathrm{max.}}$ can very nearly attain its maximum value of unity when a very pure single crystal is magnetised to saturation along a [100] crystal direction; [8] and that in association with other directional anomalies of the type discussed in section (27) it can descend puzzlingly below its theoretical minimum value when a single crystal is saturated along a [111] crystal direction. [4] Coupled with the apparent inseparability of the knee-point from the determinant factors of residual magnetisation, this evidence points strongly to the conclusion that the maximum value of I_r is largely decided by the measure in which rotational processes become operative. This statement differs

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* This conclusion is directly confirmed by some important data on remanent magnetostriction recently established by Alexander and Swaffield. [28] Their results show that the remanent magnetostrictive strain increases but fractionally for peak values of H beyond its value at the knee-point of the virgin curve. There is thus complete parallelism between these observations of remanent strain and Ewing's observations of residual intensity.

qualitatively, if not necessarily quantitatively, from the orthodox deduction that the maximum value of I_r is a simple function of the distribution of demagnetised domain orientation [12] (*loc. cit.*, p. 289). In everyday practice, however, the observed magnitude of $B_r/B_{max.}$ for values of $B_{max.}$ above the knee will provide a useful index to the general type of lattice orientation.

(32) *The Alternating Hysteresis Loop—Theory.*

In Fig. 7, *OABCDEFG* is a diagrammatic representation of the virgin magnetisation curve for an ideal polycrystalline aggregate

FIG. 7.—Alternating Hysteresis Loop for Polycrystalline Aggregate (Theoretical).

from the demagnetised state up to just beyond the point of maximum susceptibility, *F*, which, by definition, will here coincide with the knee-point at which all the 180° reversals have been completed. In accordance with the broad conclusions of section (31) it will be assumed that 90° turns occurring beyond *F* will be reversible; the small increments of *I* along *OA*, *BC* and *DE* will be regarded as irreversible.

If the magnetising field is gradually reduced from the point G, the aggregate will progressively lose its content of reversible magnetisation and the magnetisation curve will retrace its virgin path along GF. At F the residual magnetisation of the aggregate will all be of the hysteretic type, and as H is further reduced to zero value, the curve will follow the horizontal path FL, the point L representing the externally measurable residual intensity I_r.

As the reversed field is negatively increased from its zero value at L, nothing will happen to the vectorial magnetisation of the aggregate until the field attains the negative value $H_{0[100]}$ at the point J along the horizontal LJ. The reversal of the directions of domain magnetisation in the [100] crystal-group will then produce the vertical Barkhausen jump from J to K; and so on until at the point Q the externally measurable value of I will be of equal magnitude but of opposite sign to its value at L (or F). (Reference to Fig. 1 will show that for reversed magnetisation the jumps in I at any given value of the critical field strength must be twice those recorded during virgin magnetisation.)

If the negative field is increased beyond its magnitude of $H_{0[111]}$ at Q, the magnetisation curve will follow the reversible path QR, which will be parallel to FG.

If the negative field is decreased in magnitude from point Q, the magnetisation curve will follow the horizontal path QS until at point S the attainment of a positive magnitude of $H_{0[100]}$ results in another Barkhausen jump in the [100] crystal-group along the vertical path ST, with $ST = JK$; and so on, the closed cycle of magnetisation being completed at point F, beyond which any further increase in H simply reproduces the reversible path FG. (The very small increments of irreversible magnetisation over the transition stages KM, NP, TV and XY have been ignored.)

It is well known that the energy consumed during cyclic magnetisation can be measured by the area of the closed hysteresis loop thus described; and for Fig. 7 the amount of energy so computed will be the hysteresis loss per cycle of alternating magnetisation for a maximum cyclic intensity $I_{(max.)}$ equal to the value of I at the knee-point F ($= I_k$).

It will be noted that reversible magnetisation will make no contribution to the area of the hysteresis loop and can thus have no effect on the measured hysteresis loss. This observation applies both to reversible 90° turns and to elastic rotational processes. Ideally, therefore, the loop area of Fig. 7 will represent the maximum cyclic hysteresis loss.

The points H and H' in Fig. 7 obviously correspond to the value of H ordinarily defined as the coercive force H_c; and it is clear that the magnitude of the cyclic hysteresis loss, which is usually symbolised as W_h, must be very closely related to the magnitude of the product $(I_r \cdot H_c)$. A long-familiar empiricism is thus seen to rest on a very simple and sound physical basis, so long as primary 180° reversals are chiefly concerned.

For an ideal single crystal the potential value of I_r should decrease in the ratio $1 : 1/\sqrt{2} : 1/\sqrt{3}$ for magnetisation along [100], [110] and [111] crystal directions; but the critical field strength or coercive force H_c should concurrently increase in the ratio $1 : \sqrt{2} : \sqrt{3}$. The product $(I_r . H_c)$ should thus remain constant. The cyclic hysteresis loss for an otherwise ideal single crystal should therefore be independent of the directional conditions of magnetisation, and should be determined solely by the uniformly-distributed intensity of domain-boundary imperfections throughout the lattice structure. That no approach to such conditions has hitherto been experimentally recorded must presumably be related to the subject-matter of sections (22) and (27).

(33) *The Alternating Hysteresis Loop—Observation.*

With highly purified and specially heat-treated single crystals it is possible to record a rectangular hysteresis loop very closely approximating to its ideal form,[8] but such experimental material can also reveal considerable disharmony between theory and observation where quantitative directional relationships are concerned.[21] Some of the possible reasons for this lack of accord have been adumbrated in section (27).

For commercial polycrystalline aggregates the broad agreement between prediction and practice is not unsatisfactory. For hot-rolled sheet material of the type represented by Fig. 4 the typical value of H_c (for $B_{max.} = 10,000$ gauss) was recorded as $0 \cdot 90$ oersteds, which is seen to be of the order that would be expected from the observed magnitudes of the virgin curve and the estimated distribution of lattice orientation (Table II.).

Further, the well-known relative dimensions and shape of the technical hysteresis loop can reasonably be regarded as establishing the validity of the theoretical deduction used in section (32) that during reversed magnetisation the magnitude of the primary jumps will be twice those recorded by the virgin curve. The normal characteristics of the technical loop thus appear to provide strong additional support for the view that the steep part of the virgin curve is principally concerned with 180° reversals (*see* section (7)(*c*)).

The outstanding discrepancy between theory and practice clearly arises from the existence of the translational deficiency at $H_{\mu(max)}$ (or $H_{0[111]}$), which is responsible for secondary reversals that can only be coerced during cyclic magnetisation by higher values of H than should properly be necessary (section (19)). In Fig. 7 the general effect of this deficiency can be roughly pictured by adding the areas $GFJJ'$ and $RQSS'$ to the ideal loop. These additional areas will represent the energy consumed in cyclically reversing the magnetisation of the secondary domains; they will correspond to the familiar " ears " of the technical loop.

Fig. 7 shows that, as the virgin curve flattens out rapidly above the knee, a relatively small given increment of irreversible secondary

magnetisation above the ideal knee-point F can easily result in increasingly disproportionate additions to the area of the loop and so produce the accelerated rate of increase of hysteresis loss with $I_{max.}$ which is observed to occur for values of $I_{max.}$ exceeding its knee-point value I_k.[6]   Other experimental evidence indicates that the rate of increase of the alternating hysteresis loss with $I_{max.}$ tends

Fig. 8.—Magnetostrictive Hysteresis for Polycrystalline Aggregate.

to fall away very rapidly for values of $I_{max.}$ exceeding the theoretical translational saturation intensity I_t (section (15)),[29] which is clearly what the simple theory would also predict.

Satisfactory quantitative treatment of the hysteresis effect associated with secondary reversals is obviously impossible in the absence of fuller knowledge of their precise nature and origin (section (22)); but it can reasonably be anticipated that the magnitude of the effect will forcibly reflect the lattice conditions responsible for the initial deficiency in primary reversals.

It seems to be novel to point out that the observed shape of the technical loop is intimately related to the cyclic behaviour of the 90° turns contributory to $I_{max.}$ This is, however, clearly indicated by the upper half of Fig. 8, which shows a typical magnetostrictive hysteresis loop for commercial sheet material (with $H_{max.}$ of the order of H_k).   The lower tips of the " butterfly-wings " very closely correspond to the observed value of the coercive force H_c.   If the left half of the upper full-lined portion is mirrored by the dotted construction shown, it is at once seen that the cyclic dimensional changes associated with 90° turns can readily account for the characteristic form of the magnetic hysteresis loop, which (except in weak fields) predominantly relates to the behaviour of 180° reversals involving no dimensional change.

In conjunction with section (31) the preceding considerations indicate that, other things being equal, I_r will be expected to increase as H_c decreases, because a decrease in H_c should result in an increase in the proportion of primary reversals, thus tending to the conditions which appear to promote the acquisition of irreversibility by 90° turns.   The overall effect, however, will be that of a simple transfer of a given increment of I from the ears to the body of the loop, coupled with a reduction in the width of the body, so that the net effect on the area of the loop should be favourable, and the measured hysteresis loss should decrease, as is generally observed.

Fig. 7 shows that in everyday practice a linkage is to be expected

between the virgin curve and the cyclic loop, and that the nature and extent of this linkage will vary with differences in the distribution of demagnetised domain orientation.   This effect is commonly observed, but its physical significance has hitherto been a little obscure.[30]

(34) *The Hysteresis Loop—Practical Relationships.*

Fig. 7 shows that for any given value of $B_{max.}$ the chief determinant factors of the magnitude of the coercive force, as ordinarily defined and measured, will be (*a*) the domain-boundary conditions which govern the completion of the primary reversals (and hence also the dependent magnitude of $H_{\mu(max.)}$) and (*b*) the distribution of demagnetised domain orientation.

The observed value of H_c will thus not be expected to reflect lattice conditions other than those directly related to the steep part of the virgin magnetisation curve; and it cannot therefore provide a reliable index to the cyclic hysteresis loss W_h if $B_{max.}$ involves any considerable proportion of secondary reversals (*see also* section (32)). For the same reason the observed value of H_c will not be expected to show any sensible increase for cyclic peak values of H exceeding $H_{0[111]}$ on the virgin curve, no matter how much W_h continues to increase with increase in $B_{max.}$.   The validity of these conclusions is well demonstrated by Ewing's observations on graded cyclic magnetisation [18] (*loc. cit.*, p. 106) and also by tests on composite samples of soft and hard material [30] (*loc. cit.*, p. 23).

In industrial practice, some measure of composite conditions may be present in test-samples of high-silicon sheet material in which a predominantly large grain structure is associated, as often happens, with a by no means negligible content of small grains of an outstandingly different order.   In such cases it is to be expected that the steep part of the virgin curve will chiefly reflect the behaviour of the large grains only; and a partially depressed value of $B_{\mu(max.)}$ may thus be coupled with a misleadingly low value of $H_{\mu(max.)}$.   The resulting apparent improvement in the slope of the steep part of the curve will not, however, be maintained at higher inductions; and the final result will be the not unfamiliar observation that a general betterment of cyclic power-loss performance can be accompanied by a disappointing and hitherto rather puzzling deterioration in the measured power-loss ratio for values of $B_{max.}$ broadly corresponding to the upper and lower limits of the knee region of the virgin curve.   A similar effect will clearly tend to be produced by major lack of uniformity in the lattice distribution of any other factor competent to affect the normal completion of primary reversals.

Some qualification may be needed of the statement made above that the measured value of the coercive force will depend on the domain-boundary conditions which govern the completion of primary

reversals. This statement assumes that the domain-boundary conditions which govern the reversal of virgin magnetisation are substantially of the same order as those which govern the virgin process itself; and this assumption may not always be valid. It is apparently harmless enough for the general run of polycrystalline aggregates, but it may quite conceivably not hold for single-crystal conditions. Reference has already been made (Part I.) to the anomalously high values of coercive force recorded by Cioffi and others on highly purified single iron crystals which exhibited phenomenally high values of maximum permeability.[8] Such results appear to force the conception that the process of virgin magnetisation of a laboratory single crystal may materially affect the domain-wall conditions which govern the reversal of that magnetisation. It seems necessary, in fact, to contemplate the probability that when the lattice conditions are such that the ratio $I_r/I_{max.}$ virtually attains its maximum value of unity (as in the Cioffi crystal) there may be a collateral tendency towards the attainment of conditions analogous to those outlined in the footnote to section (28), and that the observed value of H_c may then be determined by factors which cannot be related in simple fashion to the magnitudes of the virgin curve.

In conjunction with sections (32) and (33) the preceding considerations indicate that there can exist no rational physical basis for a formal continuous relationship between W_h and $B_{max.}$, and that there can be but little object in attempting to find reconciling exponents for empiricisms of the Steinmetz type (*see* discussion to the above-mentioned paper by Webb,[29] *loc. cit.*, p. 427).

(35) *Rotational Hysteresis.*

If a ferromagnetic specimen is subjected to the influence of an external rotating field which is progressively increased from zero strength, the hysteresis effect will at first be qualitatively similar to that produced by a stationary alternating field. It is to be expected, however, that as the rotating field strength is increased beyond the value of H associated with the translational end-point on the virgin curve, the mechanism of magnetisation will progressively tend to remain wholly rotational, and that the directions of internal domain magnetisation must consequently tend to maintain vectorial parallelism with the continuously changing direction of incidence of the rotating field. Above the translational end-point, therefore, there should be observed a rapidly increasing tendency for the hysteresis effect to vanish during the approach to saturation. That these expectations are realised was first experimentally shown by Baily in connection with Ewing's molecular theory [18] (*loc. cit.*, p. 327). The phenomenon is of considerable importance in the technology of rotating electrical machines and has recently been re-investigated by Brailsford.[5]

PART VII.—GENERAL CONCLUSIONS.

(36) *The Competency of the Theory.*

There seems but little room for reasonable doubt that the modern theory of ferromagnetism, in a very simple form, is fully competent to account both qualitatively and also very helpfully quantitatively for the observed characteristics of magnetisation of electrical sheet steels, and to provide reliable guidance for practical endeavour directed towards the improvement of their engineering properties.

It is not pretended, however, that the ultra-simple theoretical framework here used is other than tentative; as knowledge grows it will undoubtedly be possible to introduce many constructional refinements. The proper function of a working hypothesis is to incite the acquisition of new facts, and the present exploratory treatment, like many other ventures in speculative physics, may well render its most useful service by accelerating the revelation of its own weaknesses. '' When full stops become signs of interrogation research is stimulated and guided and further progress ultimately results.'' [31]   Nevertheless, for the particular types of ferromagnetic here considered, even the simplest principles appear to be capable of leading directly to a better understanding of the physical significance of the technical magnetisation curve, and of the nature and mode of operation of the factors which govern the magnitude of the hysteresis effect; and investigation of the applicability of those principles to other kinds of ferromagnetic material may reasonably be expected to bear good fruit.

(37) *Orientation of Future Research.*

The outstanding deficiency in present knowledge clearly relates to the nature and origin of directional variations in domain-boundary conditions, the disturbing effects of which appear to be common to single crystals and to polycrystalline aggregates (section (27)).   The solution of this problem will necessarily be associated with more exact knowledge of the nature and mode of operation of the lattice factors which govern the relative behaviour and proportionate lattice content of primary and secondary 180° reversals, and hence also the very important practical magnitudes determined in Fig. 6 by the location of the point *A* and the slope and duration of *AB* and *BK*. In this connection it may be noted that the major significance of the observed trichotomy of the steep part of the polycrystalline magnetisation curve lies rather less in its apparent ability to provide a simple alternative method of estimating lattice orientation than in the direct confirmation that it apparently affords that the magnitudes of the steep part are dominated by the

lattice factors which control the mechanism of primary reversals, the study of which can thus be helpfully segregated.

Much more also needs to be known of the nature and mode of operation of the factors, including alloying elements, which control the magnitudes of equation (1), and thereby the lattice conditions for the achievement of 90° turns, as reflected in Fig. 6 by the slope of OA—a slope which can be expected, through its effect on the slope of KM, to affect the location of T, since the magnitudes associated with the elastic mechanism of rotational magnetisation along TS must inevitably be influenced by the lattice conditions which determine the elastic characteristics of initial magnetisation.

Further, a great deal yet remains to be learnt concerning the mechanism by which differing combinations of lattice composition, plastic deformation and heat treatment operate to produce variations in the distribution both of grain and of demagnetised domain orientation in the final lattice structure. " Some hitherto unannounced complexity of deformation is needed to clarify the devious relationship between recrystallised grains and the strained crystals from which they originate." [32]

From the general experimental standpoint, the treatment will have demonstrated that one of the wisest remarks ever made about the study of ferromagnetism is that " measurements of magnetostriction can tell us more about the magnetisation process than measurements of magnetisation itself " [12] (loc. cit., p. 246). In this connection, however, the subject-matter of sections (25) to (27) seems to compel the conclusion that, in the light of what is already known, ferromagnetic measurements made on ring specimens can rarely be adequate for investigational work, and that this observation must apply with especial force where magnetostriction data are concerned.

The discussion will also have made it clear that " if we are to understand the . . . properties of macroscopic crystals, and hence of aggregates of crystals, a knowledge of the ideal crystal structure as revealed by ordinary X-ray crystal analysis is not sufficient. We require to know more than the structure of the unit cell of the crystal lattice, and new methods of investigation are much to be desired " [14] (loc. cit., p. 133). These statements were originally made in relation to the mechanical properties of crystals and their aggregates; but in view of the recognised intimate relationship between the lattice conditions which govern ferromagnetic phenomena and those which govern the processes of mechanical deformation, the same findings will manifestly apply with at least equal force to ferromagnetic research. It is, in fact, becoming increasingly clear that where ferromagnetics are concerned investigations of plastic and magnetic phenomena can usefully be regarded as closely interwoven, and that they should very largely go hand in hand. For example, translational-magnetisation curves (i.e., the hypothetical curves obtained by eliminating the effects of rotational processes), residual-intensity curves, magnetostrictive-remanence curves and low-temperature plastic-creep curves all appear to

belong to closely-related families of probability-integrals; and it is impossible not to be attracted by the thought that both theoretical and experimental work could almost certainly be very profitably directed towards establishing the linkage that can reasonably be suspected to exist between the lattice factors which control some of the phenomena of plastic creep and those which determine the magnitudes of the structure-sensitive parameters of equations (1) and (8) (*see also* Becker [16] (*loc. cit.*, p. 151)).

(38) *The Practical Goal.*

The results of the present survey can apparently be crystallised by saying that the practical goal is the achievement of an optimum location of the translational end-point (section (15)), the term optimum being used to denote a maximum value of the translational saturation intensity I_t coupled with a minimum value of H. This, in turn, will involve a similarly defined optimum location of the knee-point, coupled with optimum conditions for the completion of any balance of translational magnetisation outstanding at that point.*

From a unidirectional standpoint, the attainment of this practical goal will clearly demand :

(1) A maximum value of the saturation intensity of magnetisation;

(2) a minimum of residual plastic strain;

(3) a minimum of lattice impurities, coupled with their optimum distribution in the lattice structure;

(4) a minimum incidence per unit of volume of any other lattice inhomogeneity, whether at internal structural boundaries or at external surfaces;

(5) a maximum degree of alignment of crystal directions of easiest magnetisation parallel to the selected direction of engineering application of the external magnetising field;

(6) a maximum degree of alignment of the directions of demagnetised domain magnetisation parallel to the selected crystal direction of easiest magnetisation, coupled with optimum conditions of domain size and shape, whatever these may ultimately be found to be;

(7) a minimum value of the saturation magnetostriction coefficient for crystal directions of easiest magnetisation; and

(8) a minimum value for any unenumerated factor that may tend either to retard the achievement of $180°$ reversals, or to increase the mean internal lattice stress which opposes the magnetostrictive dimensional changes associated with $90°$ turns.

* To facilitate practical discussion, it would probably be convenient to introduce the symbol μ_t to denote the permeability at the translational end-point as approximately determined by the method of Table IV., and the symbol μ_k to denote the knee-point permeability with the knee-point approximately located as in section (21).

Of these conditions only the last three are in any way novel; but the measure in which the present investigation has achieved its main objects must obviously be largely judged by the extent to which it has succeeded in establishing a coherent and rational basis for everything that is already empirically familiar. Moreover, where " technical advances " are concerned " there is all the difference in the world between pure empiricism, and experiments guided by some theory, however vague and inadequate, in directions which are likely to be profitable." [3]

It will be realised that the unidirectional standpoint from which the above ideal conditions have been derived must be very largely confined to transformer steels, and that it cannot be adopted where the engineering problem relates to the equally important tonnage of sheet material used in the manufacture of circular laminations for rotating machines. For such purposes, with current technical practice, marked directional properties are unwanted, and the ideal material should be magnetically isotropic. Whether simulated isotropy can ever be attained in a polycrystalline cubic aggregate is a matter for the future. The immediate consideration is that for much of present-day electrical-engineering design the simultaneous satisfaction of all the ideal conditions would not yield an ideal product. The usefulness of even a much improved cold-reduced strip product will therefore be strictly limited, and especially in Britain, where the preferred system of generation and distribution of electrical energy presents obstacles to the adoption of the wound-core type of transformer, which has been specially developed in the United States for the wider and more effective utilisation of the " one-way " properties of such material.

In the course of time, some of the above-stated ideal conditions may need to be modified. For example, when (and if) lattice perfection is industrially approached, it may not be possible to ignore the pyrrhotitic potentialities envisaged in section (34), in connection with which it is clearly not justifiable to dismiss as without significance Cioffi's (1932) observations that highly-purified polycrystalline specimens, although markedly inferior in maximum permeability, consistently yielded coercive-force values only a fraction of those recorded on similarly purified single crystals.[8]

Further, the present simplified treatment has not called for more than passing reference to the fact that the response of a ferromagnetic to an external magnetising field is far from instantaneous (*see* section (7) (*b*)). The complete problem, however, involves all three of the " rheological " factors of stress, strain and time. The early observations of Rayleigh and Ewing on magnetic viscosity showed quite clearly that the time-lag in magnetisation increases sharply as lattice imperfection decreases [18] (*loc. cit.*, p. 127). Cioffi also found that even in his polycrystalline specimens periods of the order of one minute were required for the completion of flux build-up [8] (*loc. cit.*, p. 377). Positive indications thus exist that optimum

conditions for practical cyclic magnetisation will demand a finite measure of magnetic springiness, and that the intrusion of any appreciable element of viscosity will disturb the static relationships between maximum cyclic induction and peak field strength. Sooner or later, therefore, the time factor may become of no little moment.

(39) *Economic Aspects.*

The ideal conditions of section (38) have perforce been framed in the most general terms, and it is not within the scope of the present survey to discuss either their everyday interpretation or the potential ways and means of achieving them. It seems reasonably certain, however, that there is but little prospect of finding " short cuts " through the ferromagnetic lattice and that the practical approach to optimum conditions will be costly.

In the existing commercial product the lattice content of the most harmful interstitial impurities has already been reduced to the order of two or three parts in ten thousand ; and since it is clear that in the soft ferromagnetic lattice it is the last step which counts, it seems improbable that the technical attainment of laboratory standards can be associated with a linear relationship between performance and cost. It is thus easily conceivable that the ultimate practical problem may not be one either in applied physics or in experimental metallurgy but in the economics of the generation and distribution of electrical energy.

An up-to-date review of the properties of available electrical sheet steels might be interpreted as suggesting that the electrical engineer always finds himself in a position to utilise improved sheet quality to good advantage ;[33] but that other considerations may be involved is evidenced by the fact that the availability of the highest grades of transformer sheet material has normally been considerably in excess of the engineering demand, notwithstanding the authoritative admission that " the capitalised cost of iron loss may greatly exceed the bare cost of the transformer."[34] It is therefore to be suspected that in the past the excessive incidence of " capitalised " iron losses in relation to prime iron cost has not been universally recognised. That this suspicion is not entirely groundless has very recently been confirmed by some provocative economic argument.[35]

data referred to in the footnote to section (31); to thank Dr. F. Brailsford, of the Research Department of the Metropolitan-Vickers Electrical Co., Ltd., for the independent data relating to Fig. 5 (including the basic saturation-torque analyses used in computing Tables V. and VI.); and to record his appreciation of the encouragement given to the survey by the Board of Directors of Messrs. John Lysaght, Ltd., and of their permission to publish.

It is to be understood, however, that those to whom the author is indebted do not necessarily endorse any unorthodox views which he may have expressed and for which he alone is responsible.

APPENDIX.—*Symbols Used in the Paper and Their Definitions.*

A.—*Orthodox Symbols.*

I = externally measured intensity of magnetisation of a ferromagnetic specimen (magnetic moment per unit of volume).

I_s = saturation intensity of magnetisation.

B = externally measured magnetic induction.

H = externally measured magnetising field strength.

$(B - H)$ = ferric induction = $4\pi I$.

$(B - H)_s$ = saturation value of ferric induction = $4\pi I_s$.

k = susceptibility = I/H.

μ = permeability = B/H.

k_0 = initial susceptibility = value of k when H is vanishingly small.

μ_0 = initial permeability = value of μ when H is vanishingly small.

$k_{\text{max.}}$ = maximum susceptibility = value of k when I/H is a maximum.

$\mu_{\text{max.}}$ = maximum permeability = value of μ when B/H is a maximum.

μ_d = differential permeability = value of dB/dH at any point on a B/H curve.

$I_{k(\text{max.})}$ = value of I when I/H is a maximum.

$B_{\mu(\text{max.})}$ = value of B when B/H is a maximum.

$H_{k(\text{max.})}$ = value of H when I/H is a maximum.

$H_{\mu(\text{max.})}$ = value of H when B/H is a maximum.

$I_{\text{max.}}$ = maximum (or peak) intensity for cyclic magnetisation.

$B_{\text{max.}}$ = maximum (or peak) induction for cyclic magnetisation.

$H_{\text{max.}}$ = peak field strength for $I_{\text{max.}}$ (or $B_{\text{max.}}$).

I_r = residual intensity for reversed magnetisation to $H = 0$.

B_r = residual induction for reversed magnetisation to $H = 0$.

H_c = coercive force = reversed field strength required to reduce I_r to zero.

W_h = hysteresis energy loss per cycle of alternating magnetisation.

$\lambda_0 (\lambda_{100})$ = saturation magnetostriction coefficient for [100] crystal direction.

B.—*Unfamiliar Symbols.*

$\left.\begin{array}{l} H_{0[100]} = \\ H_{0[110]} = \\ H_{0[111]} = \end{array}\right\}$ critical field strength for 180° reversals in [100], [110] and [111] crystal directions, respectively.

$\left.\begin{array}{l} k_{0[100} = \\ k_{0[110]} = \\ k_{0[111]} = \end{array}\right\}$ initial susceptibility in [100], [110] and [111] crystal directions, respectively.

$k_{0(a)}$ = initial susceptibility of polycrystalline aggregate.

I_t or B_t = translational saturation value.

B_π = potential B for completion of primary 180° reversals.

$B_\pi{}'$ = observed B for completion of primary 180° reversals.

$H_\pi{}'$ = observed field strength for $B_\pi{}'$.

$\mu_{0(a)} =$ initial permeability of polycrystalline aggregate.
$\mu_{\pi/2} =$ differential permeability for $90°$ turns only.
$B_k =$ knee-point B.
$I_k =$ knee-point I.
$H_k =$ knee-point H.
$\mu_t =$ translational permeability (at B_t).
$\mu_k =$ knee-point permeability (at B_k).

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Note.—This list of references is not exhaustive. It has been confined to publications readily accessible in English. Many of the papers cited give useful details of earlier work and original sources. In addition, the following cover the general ground and contain excellent bibliographies :

STONER : " Magnetism and Matter," Chapter XI. London, 1934 : Methuen.
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STONER, in his 1944 " Kelvin Lecture " to the Institution of Electrical Engineers on " Magnetism in Theory and Practice," which was delivered after the present paper was written, has also reviewed the present status of ferromagnetic theory in its more generalised relationships to industrial applications.

FOULING OF SHIPS' BOTTOMS: IDENTIFICATION OF MARINE GROWTHS.[1]

By the MARINE CORROSION SUB-COMMITTEE.[2]

(Figs. 2 to 45 = Plates X. to XVII.)

Paper No. 14/1944 *of the Corrosion Committee (submitted by the Marine Corrosion Sub-Committee).*

Contents

(1) Objects of this Paper.

The objects of this paper are :

(1) To emphasise the deleterious effects of fouling on the operation of a ship,

(2) to give a brief account of the settlement and growth of the marine organisms which are mainly responsible for fouling,

(3) to discuss briefly the methods of anti-fouling research, and the means of preventing fouling, and

(4) to describe the characteristics of marine growths in sufficient detail so that they may be correctly identified when present on ships.

A questionnaire in the form of a dry-docking report is provided on pp. 153 P–154 P. This form, additional copies of which may be obtained from the Secretary of The Iron and Steel Institute, is intended to serve as a research tool in furthering our knowledge of the growths on ships in relation to the various factors concerned. It is hoped that as many shipowners as possible will make use of this docking report.

[1] Received November 16, 1943.
[2] A Sub-Committee of the Joint Corrosion Committee of The Iron and Steel Institute and the British Iron and Steel Federation reporting to the Iron and Steel Industrial Research Council.

(2) The Significance of Fouling.

The fouling of ships by marine growths is a matter of very great importance in both the performance and the upkeep of the Royal Navy and merchant fleets.

For design purposes it is the practice of the Admiralty to allow an increase of frictional resistance of $\frac{1}{4}\%$ per day out of dock in temperate waters and $\frac{1}{2}\%$ per day in tropical waters. These figures are based on the results of experience over a number of years, and may be regarded as covering the worst conditions of fouling that are generally experienced in warships in peace-time, when a relatively large proportion of time is spent in harbours. The possible effect of fouling in producing increased fuel consumption and loss of speed is shown in Table I., which is calculated on the basis of this Admiralty allowance for various types of ships in temperate waters. The corresponding figures under tropical conditions would be approximately doubled.

Table I.—*Effect of Fouling for Six Months out of Dock in Temperate Waters.*

Frictional resistance assumed to increase $\frac{1}{4}\%$ per day.

Type of Ship.	Standard Displacement. Tons.	Loss of Maximum Speed. Knots.	Percentage Increase in Fuel Consumption * to Maintain a Speed of—	
			10 Knots.	20 Knots.
Battleship	35,000	$1\frac{1}{2}$	45	40
Aircraft carrier	23,000	$1\frac{1}{4}$	45	40
Cruiser	10,000	$1\frac{1}{4}$	50	45
Destroyer	1,850	2	50	35

* These figures are based on the fuel consumptions for propulsion only, *i.e.*, auxiliaries are not included.

The foregoing examples refer to warships under peace conditions. The corresponding figures for merchant ships will in general be less, because they spend a greater proportion of time at sea and are therefore less exposed to fouling conditions. During the war, however, many serious cases of fouling of merchant ships have been reported, particularly on vessels operating in the tropics. As a result, the Ministry of War Transport and shipowners have been considering the possibility of using more efficient compositions to meet these conditions.

Whilst it is difficult to give a reliable estimate, it is probable that at least 20% of the total quantity of fuel used for ship propulsion is expended in overcoming the increased resistance due to fouling. When to this is added the cost of the more frequent dry-dockings necessary for cleaning and coating bottoms, some idea can be obtained of the enormous expenditure attributable to fouling. Apart from the

PLATE X.

SEAWEEDS AND HYDROIDS.

Rather less than Natural Size.

Fig. 2

Fig. 3

Fig. 4

Green Seaweeds

Fig. 5

Fig. 6

Brown Seaweeds

Fig 7

Fig 8

Red Seaweeds

Fig. 9
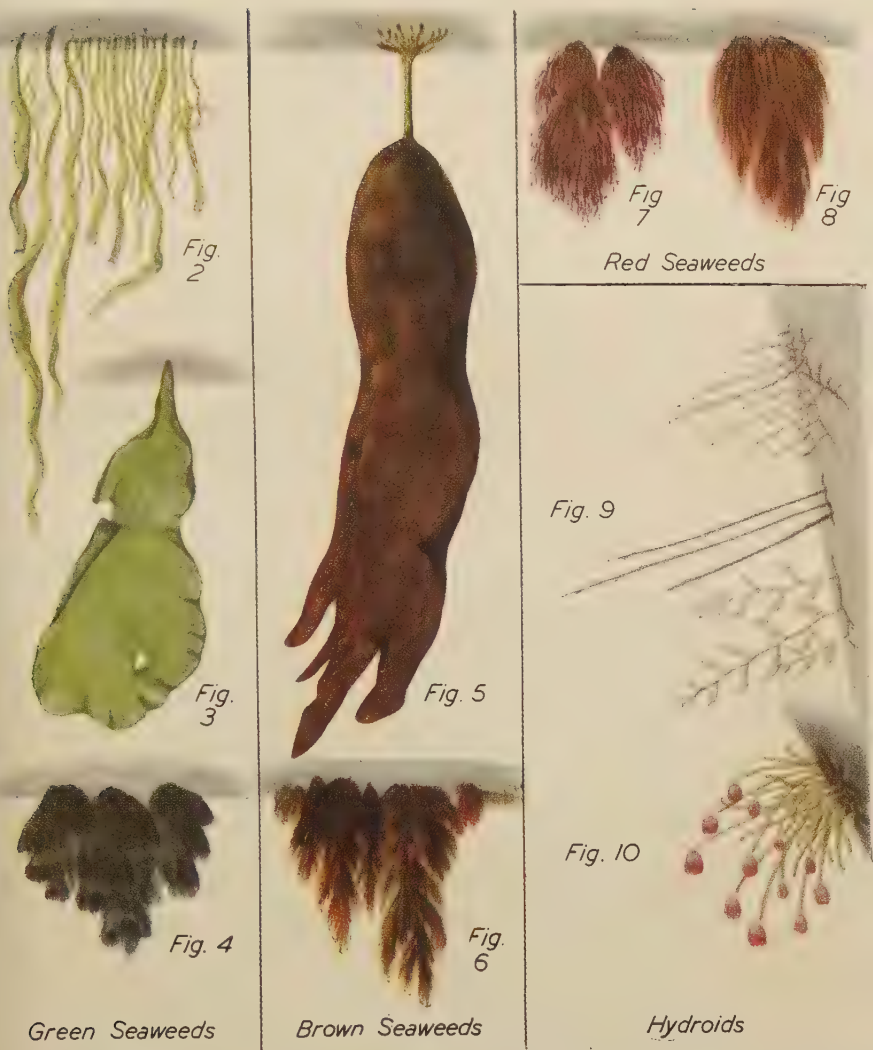
Fig. 10

Hydroids

Fig. 2.—*Enteromorpha.*
Fig. 6.—*Ectocarpus.*
hydroids.

Fig. 3.—*Ulva.*
Fig. 7.—*Ceramium.*
Fig. 10.—*Tubularia* (a common hydroid).

Fig. 4.—*Cladophora.*
Fig. 8.—*Polysiphonia.*

Fig. 5.—*Laminaria.*
Fig. 9.—Various

PLATE XI.

Various Animal Fouling Organisms.

Rather less than Natural Size.

Fig. 11

Tubeworms

Fig. 13

Fig. 14

Mussels and Oysters

Fig. 12

Barnacles

Fig. 15

Polyzoa

Fig. 16

Bases of Barnacles
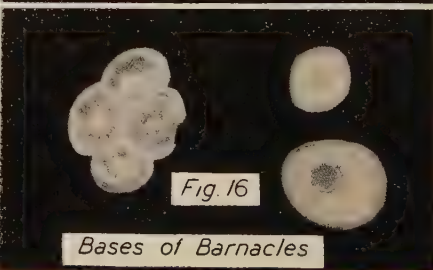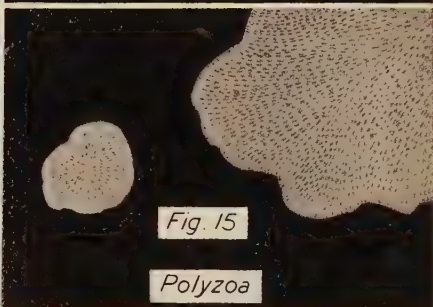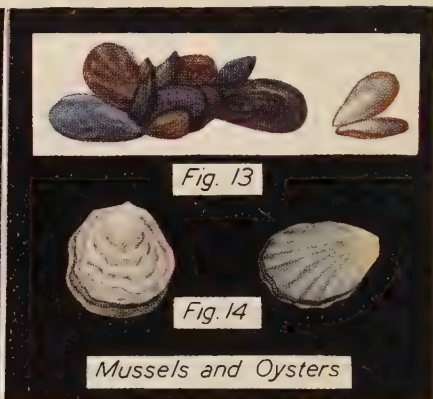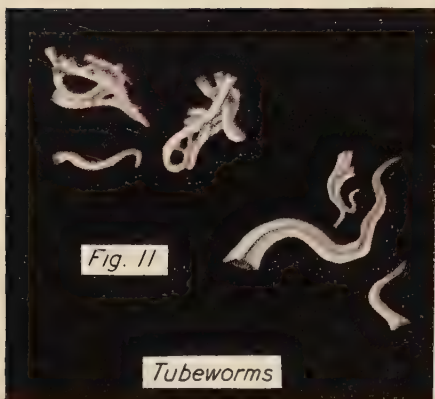
Fig. 11.—Tubeworms. **Fig. 12.**—Barnacles. The coloured type is a tropical and sub-tropical form; the white ones are a typical British species. The elongated form assumed when the barnacles are tightly packed is also shown. **Fig. 13.**—Mussels. **Fig. 14.**—Oysters. **Fig. 15.**—Patches of encrusting *Polyzoa*. **Fig. 16.**—Bases of barnacles after the barnacles themselves have fallen off or been removed by scraping.

[*Fouling of Ships.*

PLATE XII.

ACTUAL FOULING OBSERVED IN DRY-DOCK.

Fig. 17.—A heavy tubeworm infection as seen on the actual vessel in dry-dock.

Fig. 18.—Fouling of propeller of H.M.S. *Fowey* by calcareous tubeworms. (Reproduced, by courtesy, from G. D. Bengough and V. G. Shepheard, "The Corrosion and Fouling of Ships," *Transactions of the Institution of Naval Architects*, 1943, vol. 85, p. 1.)

PLATE XIII.

ACTUAL FOULING OBSERVED ON EXPERIMENTAL PANELS.
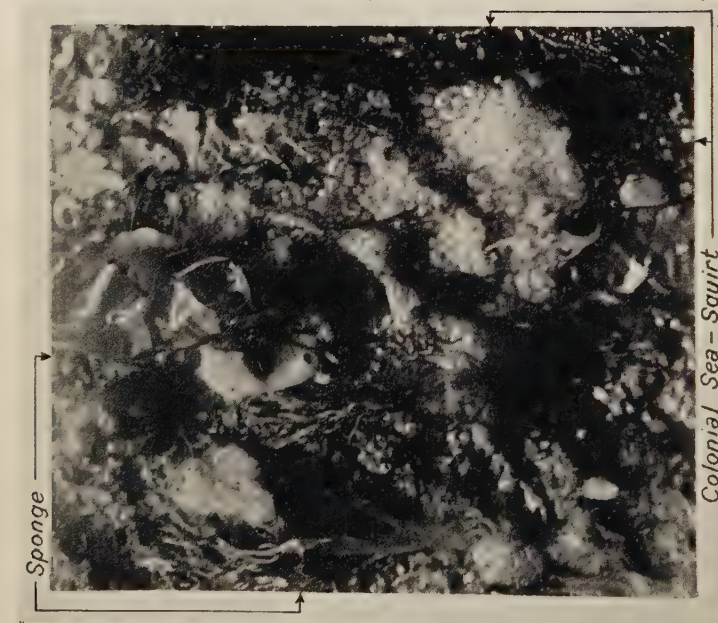
Fig. 19.—Soft-bodied animals: sponges and a colonial sea-squirt. Reproduced from a colour photograph.

Sponge ——

Colonial Sea - Squirt

Fig. 20.—A heavy infection by sea-squirts of a panel fouled at Gosport.

[Fouling of Ships.

PLATE XIV.

VARIOUS ANIMAL FOULING ORGANISMS.

Fig. 21.

Stalk

Fig. 23

Fig. 22

Head with Shell

Fig. 24

Fig. 25

Fig. 26

Fig. 27

One Inch
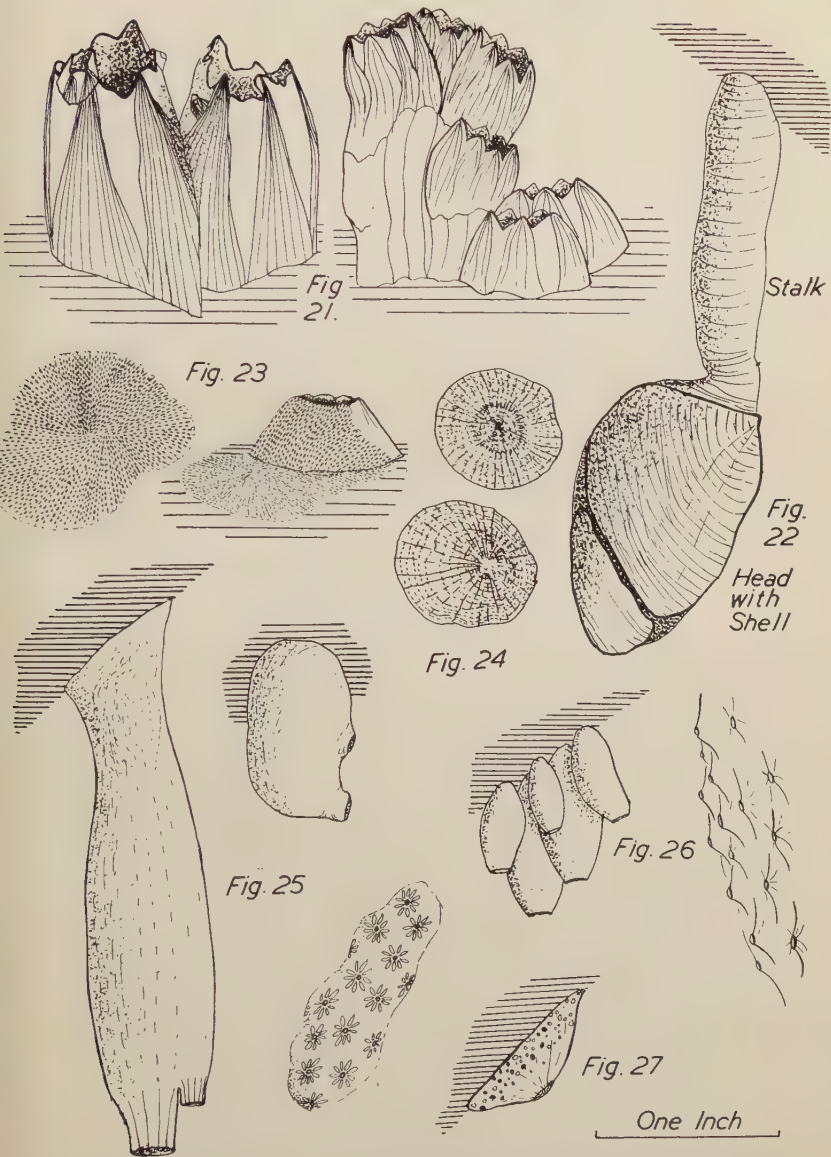
Fig. 21.—"Acorn barnacles," showing the compressed forms found in crowded colonies.
Fig. 22.—The "goose barnacle." Fig. 23.—Patches of an encrusting *Polyzoan*, showing how it may grow over the shell of a dead barnacle. The structure is honeycomb-like. Fig. 24.—Barnacle bases, showing the type of markings which distinguish them from *Polyzoa* patches.
Fig. 25.—Various sea-squirts, showing two different forms of single animals and a colonial form.
Fig. 26.—Sponges, showing (*left*) a colony of single individuals, and (*right*) a colonial "encrusting" sponge. Fig. 27.—A sea-anemone in its contracted form as seen out of water.

PLATE XV.

STRUCTURES OF VARIOUS PLANT FOULING ORGANISMS.
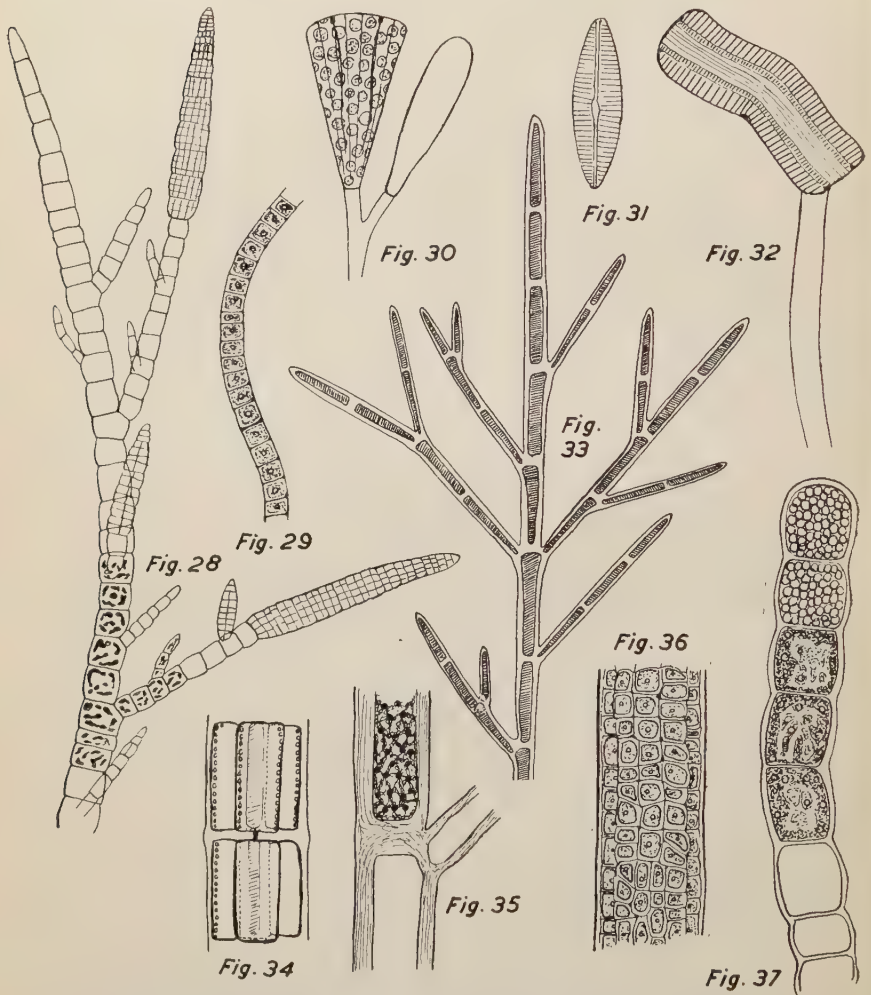
Fig. 28.—Branch of an *Ectocarpus*, with four of the characteristic reproductive organs; cell contents only shown at the base. × 100.　　**Fig. 29.**—Portion of a thread of *Ulothrix flacca*. × 150. **Fig. 30.**—Two individuals of *Licmophora*, seated on the end of the branches of the mucilage stalk and seen in different positions. × 300.　　**Fig. 31.**—Single individual of *Schizonema*. × 700.　　**Fig. 32.**—Cell of *Achnanthes* at end of mucilage stalk. × 250.　　**Fig. 33.**— Tip of a *Cladophora*, showing shape of cells and manner of branching. × 100.　　**Fig. 34.**— Two tiers of a *Polysiphonia*, with four peripheral cells surrounding the single central one. × 400. **Fig. 35.**—Small part of a *Cladophora* at a point of branching, showing cell contents and the thick walls. × 350.　　**Fig. 36.**—Small part of a strand of *Enteromorpha*. × 150.　　**Fig. 37.**— Tip of a thread of *Urospora*; the two uppermost cells with reproductive cells. × 150.

PLATE XVI.

PHOTOMICROGRAPHS OF VARIOUS SEAWEEDS.
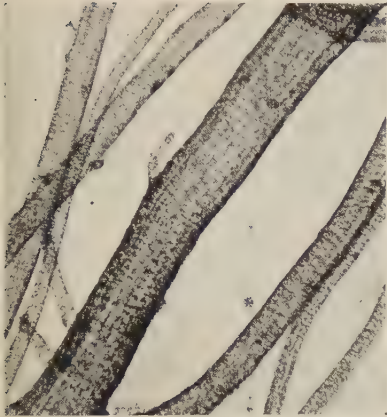
Fig. 38.—A number of strands of *Enteromorpha*. × 70.

Fig. 39.—Part of a plant of *Cladophora*, showing the elongated cells. × 30.
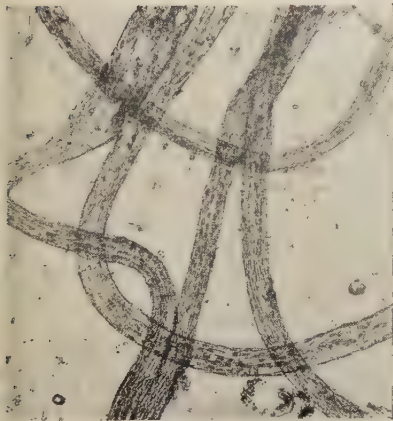
Fig. 40.—The diatom *Schizonema* in its mucilage tubes. × 70.

Fig. 41.—The brown seaweed *Ectocarpus*, showing a number of the reproductive organs. × 30.

PLATE XVII.

PHOTOMICROGRAPHS OF SEAWEEDS AND *POLYZOA*.

Fig. 42.—The red seaweed *Ceramium*, showing the characteristic banded appearance and pincer-like endings. × 15.
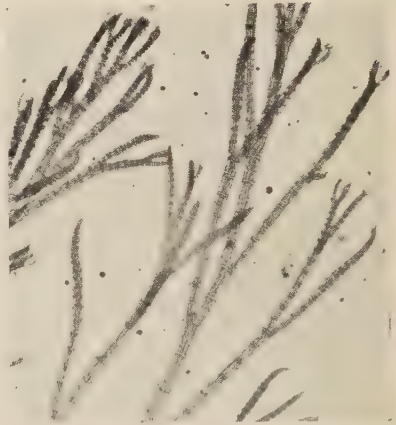
Fig. 43.—The red seaweed *Polysiphonia*, showing the tiers of cells. × 30.

Fig. 44.—A branching *Polyzoan*. × ⅔.

Fig. 45.—The same organism as in Fig. 44, showing the typical honeycomb structure of the *Polyzoan*. × 4.

[*Fouling of Ships.*
[*To face p.* 145 P.

purely economic aspect, the problem is one of vital national import-ance in war-time from an operational point of view. The outcome of a naval engagement might well depend on the increased endurance and higher maximum speed that would result from a reduction of fouling.

(3) The Growth of Fouling.

When a plate painted with a non-poisonous paint is immersed in the sea at certain times of the year, a community of organisms rapidly settles upon it. Included among these organisms are :

(i) Marine *bacteria*, some types of which secrete a coherent slimy film over the surface.

(ii) The young stages (spores) of *seaweeds*, microscopic in size, but many of them rapidly developing into typical seaweed form.

(iii) *Diatoms*, which are minute plant cells occurring singly, in chains or in masses. These may form a brown slimy layer over the surface or long trailing brown threads similar in appearance to certain seaweeds.

(iv) The larval forms of many sessile marine *animals*. These are all microscopic free-swimming organisms capable, at a certain sharply defined stage in their development, of settling on a suitable surface, to which they attach themselves by a cementing organ. Attachment precedes a metamorphosis pro-ducing the adult organism. As the animal grows, more cement-ing material is laid down, ever increasing the security of attach-ment. This sequence occurs with the common animal fouling organisms such as *barnacles, calcareous tubeworms, ascidians (sea-squirts)* and *polyzoa*. The attachment and growth of *hydroids* (which belong to the animal kingdom) follow a more plant-like pattern; the larva settles and grows out over the substratum as a series of branching tubes, from which at intervals arise the stalks bearing the main body and feeding organs of the animal.

A heavily fouled surface may show a basal " carpet " of bacterial and diatom slime from which project the " stalks " of hydroids as well as diverse seaweeds, and sometimes the trailing brown filaments of certain diatoms. Barnacles, tubeworms and many other animal forms attach themselves very firmly to the paint surface, for this purpose penetrating the slime, and often the surface layers of paint, if this is fairly soft.

A very heavy growth of one type of organism is frequently accompanied by the more or less complete absence of rival forms both plant and animal, so that a badly fouled surface can usually be described in terms of a very few animal or plant types. This phenomenon is known as *biological exclusion*.

Plants grow predominantly at and near the water-line, and if they are abundant there they tend to discourage most types of animal life in that area.   Well below the water-line, and particularly under the turn of the bilge, lack of light prevents plant growth and the population is largely, if not entirely, animal.

Several factors influence the degree of fouling which may appear on a non-toxic surface; the more significant of these include the season of the year, the amount of light reaching the submerged surface, the temperature of the water, and, perhaps the most important, the geographical location of the waters concerned.   The colour of the painted surface is relatively unimportant.

Many fouling organisms have a restricted breeding period; this is illustrated in Fig. 1, which has been compiled at two observational

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
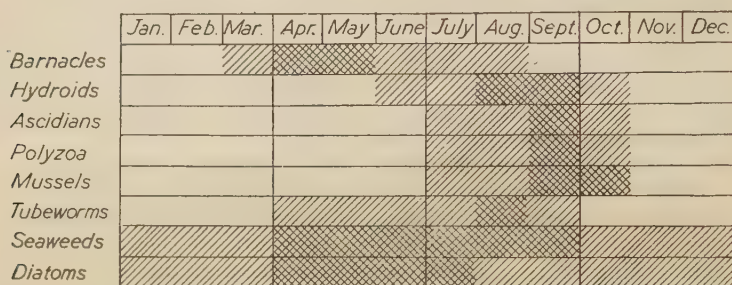
Fig. 1.—The Fouling Season at Caernarvon and Millport 1941–42.   Heavy settlement is indicated by cross-hatching, the period of lighter infection by single hatching.   (*Ascidians* = sea-squirts.   *Diatoms* correspond chiefly to those inhabiting the *slime* layer on ships.)

stations, Caernarvon and Millport, during the two years 1941–42. The seasonal settlement of fouling organisms naturally varies according to the locality, but the diagram may be taken as being indicative of behaviour around the coasts of Great Britain.   In some tropical ports, it is known that the seasonal variation in settlement is much less marked than in home waters and that extensive fouling will occur nearly all the year round.

Fouling occurs when ships are in port or at anchor in shore waters, since the usual fouling organisms live in or near shore waters.   The ports of the world vary considerably in their liability to produce fouling.   As a rule, ports in the tropics are more troublesome than those in temperate climates.   Most marine fouling organisms will not survive in fresh water, and hence in ports into which river waters run the variety of plant and animal life that may appear is curtailed or that acquired in a sea-water port may perish and sooner or later fall off.   The shells of barnacles and tubeworms remain attached to the ships long after the animal is dead, but become very brittle.   One species of barnacle (*Balanus improvisus*) is reputed to

have caused severe fouling in almost fresh water (*e.g.*, the river Plate).

(4) THE ANTI-FOULING PROBLEM.

The present-day method of combating fouling on the under-water plating of ships is the use of anti-fouling compositions applied just prior to undocking. These compositions may contain as poisons copper and mercury compounds and organic substances. In water, these poisons leach out of the paint medium, so that a more or less continuous supply of poison is available at the surface of the paint film. The value of an anti-fouling composition depends on the rate of leaching of the toxic ingredients, which in turn is a function of the type of medium employed to bind the paint and of the percentage of toxic ingredients present. All anti-fouling compositions thus have a limited life, which for most commercial products is of the order of 4–12 months. Thus, periodical renewals of anti-fouling compositions are determined by this limited life.

The actual anti-fouling mechanism is being actively investigated at the present time. Available evidence indicates that the toxicity of a surface has little effect on the growth of an organism once attachment has taken place, so that the main line of attack lies in the prevention of the initial attachment. The constituents of the anti-fouling composition may thus include substances which exert a repellent or lethal action on the larvæ and spores, or alternatively substances which prevent the adhesion or setting of the cementing substances produced by many of the organisms for effecting the attachment. It is also possible to eliminate attachment by exfolia-tion, *i.e.*, the continual shedding of the surface layer of a suitably compounded paint.

A brief summary of the Sub-Committee's investigations which are now in progress on this matter will be appropriate. Tests are being made on formulated anti-fouling compositions containing inorganic and organic poisons. It has been found that mercury is approximately twice as effective as copper against weed fouling (weight for weight) and three times as effective against barnacle fouling. Inorganically combined arsenic is almost ineffective. Although many organic poisons have been found which are very much more potent than copper and mercury when in solution in sea water, unfortunately in most cases this toxicity is difficult to bring into effect when the organic poison is incorporated in a paint film. There are, however, certain promising developments in this connection. A new technique has been developed for studying the leaching rate of poisons from paint films immersed in sea water.

An important aspect which is receiving consideration is the paint medium in which the poisons are incorporated, due regard being paid to the conflicting requirements that the poisons shall be readily and continuously available whilst the coating shall be as durable as

possible. In all this work the importance of providing efficient protective undercoats has been stressed, since premature failure of the undercoats invariably leads to unrestricted fouling, apart from the incidence of corrosion troubles.

It will be realised that the problem of fouling is indeed a complex one requiring the collaboration of the marine biologist and other specialists. It is equally desirable that all those who are concerned with ships and shipping at sea or in dock should be familiar with the broader aspects of the problem and the methods by which it is being tackled. It is hoped, therefore, that this paper will serve a useful purpose in stimulating the interest and co-operation of all concerned, and at the same time provide a useful guide to the identification of the marine organisms which cause fouling.

(5) The Fouling Organisms.

On a ship that has remained for a long period of time in a harbour and is then dry-docked, perhaps in that same harbour, without an intervening sea voyage, an enormous number of different types of organisms may be found growing. Not all of these forms are attached to the surface of the vessel, for in the miniature forest of growth all sorts of creeping and swimming forms find a comfortable berth. In. addition, many of the attached forms have anchorages which will not stand up to the rapid motion of a ship at sea. In this paper attention will be concentrated on those forms which are likely to be found in the normal course of a vessel's work, when she is dry-docked at the end of a trip with relatively little opportunity for the settlement of the temporary lodgers which may occur in the harbour and approaches to dry-dock areas.

The limitation of the description to the " permanent " lodgers has two advantages : There are surprisingly few types to describe, which simplifies the problem of identifying them ; also, since the temporary inhabitants will all be rapidly washed off when the ship puts to sea, they are not important in causing resistance to the motion of the ship.

Marine fouling growths appear either as *slimes*, as tresses of marine *plants* or in the highly individual forms shown by the marine *animals*. The animals and slime may occur over the whole submerged surface ; the tresses produced by plant growth rarely extend more than a few feet below the water-line.

(a) *Slimes*.

The nature of the slimes that occur on ships can be recognised only by microscopic examination. Commonly they appear structureless under a magnification less than $\times 100$, and such slimes are probably formed by *bacteria*. Others, which are usually rather tougher, are formed by one-celled plants called *diatoms*. They live

in countless numbers, often closely packed together, within the slime which they themselves produce (*see* Fig. 40). The contents of the cells are brown or olive-yellow in colour.

(b) *Plants* ("*Weeds*").

The *seaweeds* that form the "grass" on the upper parts of the underwater plating are of diverse kinds like the seaweeds found in rock pools on our own shores. They may be *green*, light or dark *brown*, bright *red* or purple in colour (Figs. 2 to 8), and may reach a length of several inches.

(c) *Animals*.

The best-known of all the animal fouling organisms (Figs. 9 to 16) are the *barnacles*. The form of these, with their conical shells adhering firmly to the hull surface, is almost too well-known to need description.

The common type of *barnacle*, the "acorn barnacle" (Figs. 12 and 21), is most usually encountered, but occasionally stalked or "goose barnacles" occur. The latter are attached to the hull by a thick muscular stalk up to 3–4 in. in length, at the end of which is the body with its shell (Fig. 22), which may be inconspicuous.

The *shellfish* (molluscs) which foul ships are represented by the *mussels* and *oysters* (Figs. 13 and 14). They are not likely to be mistaken for any other forms, since the shell is always formed from two halves called "valves." They frequently occur in large numbers on the various underwater gratings of the ship; when they grow on the hull itself they show that the anti-fouling coating has completely broken down, since they are very easily poisoned.

Tubeworms, as their name suggests, appear as white or greyish limy tubes, which may be much coiled, lying flat against the surface or sometimes projecting outwards from it (Figs. 11 and 17). They often occur in patches on the hull surface (when they are frequently but incorrectly called "coral patches"). They are of considerable importance in the fouling of propeller blades (Fig. 18). Their very long and firm attachment anchors them well even on a rapidly rotating screw, where they may occur along almost the whole length of the blade, causing a very serious reduction in the propulsive efficiency. They are fairly sensitive to poisonous paints, and hence their settlement on the hull indicates poor anti-fouling properties.

All the above forms possess shells which remain on the hull even when the animal is killed, *e.g.*, by steaming through a fresh-water zone. Other animal forms without limy shells can occur either as plant-like branching growths (*e.g.*, *hydroids*) or jelly-like *soft-bodied forms*.

Hydroids (Figs. 9 and 10) are often important fouling organisms, since they are firmly attached and some are very resistant to anti-

fouling paints. The most usual forms occur in patches or clumps of knobbed stalks, which are much stiffer than those of fouling seaweeds, so that they stand out from the hull surface even when in dry-dock. The tresses of seaweeds almost always collapse against the surface when the water is withdrawn. One of the commonest forms of hydroid in British waters (*Tubularia*, Fig. 10) has a very striking bright pink head to the stalk. These heads disappear under unfavourable conditions (*e.g.*, fresh water, low temperature, &c.), but the stalks persist and form characteristic stiff, wiry grey clumps.

The *soft-bodied forms* include the *sponges* (Figs. 19 and 26), *sea-squirts* (Figs. 20 and 25) and *sea-anemones* (Fig. 27).

(6) The Identification of Fouling Organisms.

It is impossible to give an absolutely hard and fast rule for the identification of any particular type of fouling organism. The key in Section (7) gives a reasonably accurate method of establishing the principal groups without going into detail, which can be seen only under a hand-lens or microscope. Whenever doubtful cases occur, a small sample can readily be preserved in water to which a few drops of formalin have been added. The Marine Corrosion Sub-Committee will gladly examine and identify any specimens sent to them, and will supply tubes of formalin to anyone wishing to send samples; correspondence on this subject should be addressed to the Secretary of The Iron and Steel Institute.

In using the dry-docking report, the following general remarks should be borne in mind. *Seaweeds* are almost always confined to the water-line area; if a plant-like growth occurs over the whole or the darker parts of the hull it is probably a *hydroid*. A green colour is an almost certain mark of a seaweed, but the latter may also be red or brown. A red seaweed is usually of a fairly rich deep colour, the stalk as well as the " branches " being all of one colour. The red colour of some hydroids is limited to the knobbed head alone; the stalks (which may not bear any head at all) are usually greyish, brown or white. A diatom slime may look like a patch of brown oil; it is not, however, greasy, and washes off the fingers easily with water; when dry it often appears as a grey or greenish-grey film.

The recognition of the various kinds of plant growths, both diatoms and seaweed, that occur on fouled vessels is most satisfactorily accomplished by the use of the microscope, a magnification of 100 diameters being adequate for this purpose. Some seaweeds are, however, difficult to distinguish from one another except by an expert. Some identification is possible by examining plant growths with a good hand-lens; for this purpose it is advisable to spread them out thinly on the fingers or in water between two small sheets of glass, examining them against a strong light.

(7) Dry-Docking Report and Key.

A reduced facsimile dry-docking report, which has been filled in for purposes of illustration, is given in the following four pages. Blank copies of this report, printed foolscap size and incorporating the appropriate keys for identification of the organisms, are issued separately and may be obtained from the Secretary of The Iron and Steel Institute.

(8) Notes on the Recognition of Specific Organisms.

(a) *Diatom Slimes*.

Among the types of diatoms responsible for fouling are species of *Schizonema*, in which numerous individuals live within a branching system of mucilage tubes (Fig. 40). The individual cells, according to the position in which they lie, appear rectangular or more usually boat-shaped, tapering from the middle towards each end (Fig. 31). Other diatom slimes are of a different character, the cells being situated at the ends of rather thick, simple or branched, transparent mucilage stalks, which are themselves attached to the ship's hull. The commonest of these, due to a diatom called *Achnanthes*, is readily recognised ($\times$ 50), because the individual cells either appear oval or exhibit a marked bend in the middle (Fig. 32), according to the side which faces the observer. Less frequently diatoms are found with wedge-shaped cells borne on mucilage stalks. These, *Licmophora* (Fig. 30), usually grow attached to other seaweeds. Many other kinds of diatoms occasionally occur in the growths on fouled vessels, but these are rarely abundant and could only be identified by an expert.

(b) *Plants*.

Among the *green* seaweeds the commonest is *Enteromorpha* (Figs. 2 and 38), which possesses soft and rather flexible threads, frequently unbranched, although a few kinds branch freely. Under the microscope ($\times$ 50) the threads can be seen to resemble a hollow green tube, a layer of small cells surrounding the central hollow. The cells are commonly arranged in longitudinal rows (Fig. 36). In some of the coarser kinds the tube-like character is recognisable without microscopic examination. The strand of *Enteromorpha* may grow to a length of 6 in. or more.

Less commonly the green seaweed *Cladophora* (Figs. 4 and 39) is concerned in fouling. This occurs in dense tufts, which are richly branched and usually from 1 to 2 in. long. They have a coarser " feel " than the growths of *Enteromorpha*, and with a good hand-lens can be seen to consist of simple rows of long cells (Fig. 33), much larger than those forming the surface of the *Enteromorpha* tube. The branches commonly arise in twos or threes at the same point (Fig. 33).

Occasionally green fouling is due to *Urospora*; this has un-branched hair-like threads, which, when handled, have a rather slimy feeling. Structurally (× 100) they show a single row of broad, often barrel-shaped, cells with rather thick walls and dark green contents (Fig. 37). The shape and size of the cells are very variable.

In the early stages of fouling very much narrower threads with small cells are sometimes found; they belong to the seaweed *Ulo-thrix flacca* (Fig. 29), and are recognisable only under a microscope (× 100). Such threads sometimes occur within the diatom slimes.

Species of sea lettuce (*Ulva*) may also be met with on ships' hulls, although, so far as present experience goes, they always occur in

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KEY TO SECTION A OF DRY-DOCKING REPORT.

(1) *Organisms with a Shell.*

    (*a*) Conical shells with an opening at the top ("acorn barnacles") . . . . . .

    (*b*) Shells (formed from many plates) at the top of } BARNACLES. a long fleshy stalk ("goose barnacles") .

    (*c*) Small but long tubular shells, lying flat or projecting upwards at the open end, often coiled . . . . TUBEWORMS.

    (*d*) Paired shells (like mussels and oysters) . . MOLLUSCS.

(2) *Organisms with no Shell.*

    (*e*) Bag-like forms or slimy rounded masses . . SOFT-BODIED ANIMALS.

    Branching types :

    (*f*) *Stiff* stalks, dark brown, grey or white in colour, sometimes ending in knobbed heads . . HYDROIDS.

    (*g*) Green, brown or red, often branched threads or leafy growths, *limp* (*i.e.*, lying flat in dry-dock) and near water-line . . . . . SEAWEED.

The above key is sufficient for the identification of all the groups distinguished in Section A of the dry-docking report.

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association with some of the other green forms. One of the common-est kinds grows in broad sheets of about the thickness of tissue paper and is readily recognised (Fig. 3), but some kinds of *Ulva* produce relatively narrow ribbons that are not always easily distinguished from some types of *Enteromorpha*.

Of the *brown* seaweeds responsible for fouling one of the very commonest is *Ectocarpus*, of which there are a number of different kinds. Its tresses are usually dark brown, and when spread out are seen to be richly branched (Figs. 6 and 41). Some kinds are less than an inch long and, if there is a dense growth of *Enteromorpha*, for instance, may be completely hidden beneath it. Other kinds of *Ectocarpus* may grow to a length of several inches. Under the microscope the contents of the cells appear brown or yellowish-brown, although if the vessel has been for some hours in a fresh-water

DRY-DOCKING REPORT.

This form, together with any samples collected, should be sent to: The Secretary, The Iron and Steel Institute, 4 Grosvenor Gardens, London, S.W. 1.

Name of Vessel : *S.S. HESPERUS.*

Date of Dry-docking : *30 Nov. 1943* .

Place : *BIRKENHEAD*

SECTION A.

The whole of this section should be completed as far as possible.

LAST DRY-DOCKING.

Date : *15 March 1943* .... Place : *GLASGOW*

Anti-corrosive coat : * *Smith's grey protective* .... Touch up/~~one coat~~/~~two coats~~.

Anti-fouling coat : * *Smith's Admiralty quality red* ~~Touch up~~/one full coat.

Weather when painted : *Cool but fine*

VOYAGE.

Port of Call.	Arrival Date.	Departure Date.
Alexandria	15:4:43	19:4:43
Aden	23:4:43	27:4:43
Colombo	5:5:43	10:5:43
Perth	9:6:43	12:6:43
Sydney	22:6:43	22:7:43
Durban	22:8:43	5:9:43
Freetown	26:9:43	10:10:43
Liverpool	3:11:43	

FOULING.

Kind.	Amount ‡ and Position.		
	Sides.	Bottom.	Propellers.
Barnacles . .		X X	
Tubeworms . .			X
Mussels or Oysters .		X	
Soft-bodied forms .			
Hydroids . .	X	X	
Weed (green) . .	X X		
Weed (brown) .	X		
Weed (red) . .			

‡ *The amount of fouling should be shown thus :* × *little ;* × × *much.*

PAINT CONDITION ON BOTTOM.

Paint Condition.	PORT.				STARBOARD.			
	Forward.	Amidships.		Aft.	Forward.	Amidships.		Aft.
		Above Bilge-Keel.	Below Bilge-Keel.			Above Bilge-Keel.	Below Bilge-Keel.	
Good [1]			X					
Fair [2]	X			X	X		X	X
Bad [3]		X				X		
Intact anti-fouling coating. % [4]	25	1	80	50	40	5	50	50

[1] *Good.*—Paint generally firm and adherent, rusted and bare areas not exceeding 2% of the total area.
[2] *Fair.*—Rusted and bare areas from 3 to 9% of the total area.
[3] *Bad.*—Rusted and bare areas 10% or more of the total area.
Enter a × in each column opposite the appropriate condition.
[4] Insert the percentage areas in each column.

ZINC PROTECTION BLOCKS † : ~~Not fitted~~/condition of zincs : *very badly corroded, almost disappeared on starboard side.*

OTHER COMMENTS : *Fouling generally heavy. Barnacles chiefly on areas from which antifouling coating had flaked.*

* *Enter the name of the composition and cross out remarks which do not apply.*
† *Cross out remarks which do not apply.*

port the brown colour will have leached out and the contents may look green. Some or many of the shorter branches will be found to end in oval or elliptical structures, consisting usually of several rows of minute cells, much smaller than those composing the other parts of the seaweed (Fig. 28). These distinctive structures are the reproductive organs of *Ectocarpus*.

DRY-DOCKING REPORT—*Continued*.

SECTION B.

These questions are less important than those in Section A overleaf, but answers to any or all of them will provide very useful information.

SPECIAL NOTES ON FOULING.

1. *Slime*.* Present/~~absent~~. ~~Bacterial~~/diatom.

2. *Weed*. (If individual types of weed can be identified (using the pamphlet on "The Fouling of Ships' Bottoms" or the key below) enter the names and amount (as × or × ×) of each in this space.) ...... *Enteromorpha xx at waterline with a little Ulva x. and Ectocarpus x* ....

3. *Barnacles*. Size : * Large/medium/~~small~~. Colour : * ~~White~~/purple or blue.

4. *Molluscs*.* ~~Mussels~~/oysters. ~~Bottom-plating~~/gratings only.

5. *Polyzoa*.* ~~Flat encrusting types~~/branched forms.

6. *Soft-bodied forms*.* ~~Sponges/sea-squirts~~.

7. *Any other forms*. *(Give brief description and send sample if possible.)*
...... *a few soft bodied forms ? sea anemones.* ......
...... *Sample tube enclosed* ....

8. *Special Notes* (e.g., if port and starboard sides very differently fouled or if fouling limited to certain special areas. Any information as to where fouling was first encountered on the voyage, length of weed or diameter of barnacles on docking, etc.):
.. *Green weed much heavier on port side, up to 3" long at* ....
.. *drydocking. Some fouling (weed) noticed at Perth 10-6-43* ......
.. *Barnacles up to ¾" in diameter* ....

Signature :. *D. Jones* ....   Position in Firm or ship : *Dock Superintenden.*

* *Cross out remarks which do not apply.*

Other brown seaweeds that may occur on ships' hulls are coarser and less richly branched, but these are rare and have not usually reached their full growth, and it would require an expert to name them. The most frequent is *Scytosiphon*, with hollow strands resembling those of *Enteromorpha*. The bladder-wrack (*Fucus*) and the oarweeds (*Laminaria*) (Fig. 5) are likely to settle only on a heavily fouled vessel which has made a long sojourn in port. They would almost certainly become detached when the ship began to move through the water.

KEY TO SECTION B OF DRY-DOCKING REPORT.

(See also key to Section A if required.)

(1) *Organisms with a Shell.*

   (*h*) Flat patches of a limy encrustation, honey-comb in structure .   .   .   .   .   POLYZOA.

(2) *Organisms with no Shell.*

   (i) *Branching types :*

     (*i*) Branches expanding from a single base or forming a moss-like tangle; never possessing heads on the stalks and showing a honeycomb structure under a good lens .   POLYZOA.

     (*j*) Green weeds :

       (1) Soft and flexible tubes, varying in thickness from that of human hair to about $\frac{1}{4}$ in. or more, usually little branched .   .   .   .   .   ENTEROMORPHA.

       (2) Single threads, with a slimy feeling, of the thickness of a human hair or much narrower, the individual cells in the wider threads just recognisable under a good lens .   .   .   UROSPORA.

       (3) Richly branched threads, forming tufts 1–2 in. long, with a rather harsh feeling, the long component cells readily seen with a lens .   .   .   .   CLADOPHORA.

       (4) Broad papery sheets   .   .   .   ULVA.

     (*k*) Brown weeds :

       (1) Threads forming short tufts or long hanging tresses, usually extensively branched, but the majority of the branches much narrower than those of *Cladophora*. (N.B.—These growths may appear green after a stay in fresh water) .   .   .   .   .   ECTOCARPUS.

       (2) Similar branching threads, with a more slimy and softer feeling than those of *Ectocarpus*; under a microscope are seen to consist of mucilage tubes harbouring boat-shaped diatoms .   SCHIZONEMA.

     (*l*) Red weeds :

       (1) Branched threads, often repeatedly forked, the two arms of the ultimate forks often curved inwards like a pair of tongs; threads with alternating darker and lighter cross bands .   CERAMIUM.

       (2) Branched threads, in which the elongated cells are arranged in successive horizontal rows, especially obvious in the upper parts   .   .   POLYSIPHONIA.

   (ii) *Soft-bodied forms :*

     (*m*) Jelly-like masses or transparent leathery bags   SEA-SQUIRTS.

     (*n*) Opaque bag-like or spongy structures .   .   SPONGES.

Of the *red* seaweeds likely to occur on ships' hulls the two most easily recognised are *Ceramium* (Fig. 7) and *Polysiphonia* (Fig. 8). Both appear as richly branched tresses, usually 1–3 in. long; those of *Ceramium* are mostly bright red, those of *Polysiphonia* often dark purple, sometimes appearing almost black. When the tips of the threads of *Ceramium* are examined under a hand-lens (Fig. 42) they usually appear forked, the two arms of the fork often being curved inwards like a pair of tongs. The threads themselves show numerous cross bands which are of a darker colour than the intervening portions. These two features are quite distinctive of *Ceramium*. Under a microscope (× 100) the banded appearance is seen to be due to the fact that the large cells forming the threads of this seaweed are covered at regular intervals by sheets of smaller cells.

The threads of *Polysiphonia* are usually coarser. The upper (*i.e.*, younger) parts, when viewed with a hand-lens, show an arrangement of cells in horizontal tiers which is very characteristic and is even more obvious at a magnification of × 50 (Fig. 43). The individual tiers may consist of from four to twenty longish cells (Fig. 34). The walls of the cells are usually thick. Sometimes some of the branches are irregularly swollen and harbour a number of very deeply pigmented cells, often in groups of fours; these are the reproductive cells of *Polysiphonia*.

(c) *Animals*.

When an acorn barnacle is scraped off the hull surface it generally leaves a circular plate of lime still attached to the paint (Figs. 16 and 24). There is, however, one type of fouling organism which rather closely resembles a barnacle base and should be carefully distinguished from it. This is known as a *Polyzoan* and produces another form of " coral patch " on the surface (Figs. 15 and 23). The *Polyzoan* encrustation has a fine net-like or honeycomb structure composed of numerous small cells, while a barnacle base resembles a fish scale.

Polyzoa also occur as flexible branching forms (Fig. 44), as well as in the " coral patch " form. They are difficult to distinguish from plant and hydroid growth, though their fine honeycomb structure is generally visible under a hand-lens (Fig. 45).

Jelly-like masses, found usually on ships moored for a long time in richly infested waters, may be *sea-squirts* (Figs. 19, 20 and 25) or *sea-anemones* (Fig. 27). A thick leathery bag of jelly which ejects water voluntarily or when compressed (sea-squirts), or a coloured or white flattened blob of jelly, is typical of such animals.

Sponges, sometimes found under similar circumstances, are more bag-like in structure with a rough surface. They have either a single large opening to the bag or a very large number of such openings from a colony (Figs. 19 and 26).

THE INFLUENCE OF MELTING CONDITIONS ON THE PHYSICAL PROPERTIES OF STEEL CASTINGS.[1]

By H. T. PROTHEROE, B.Sc. (THE UNIVERSITY OF SHEFFIELD).

(Table I. = Plate XVIII.)
(Figs. 10 to 15 = Plates XIX. to XXII.)

Paper No. 11/1944 of the Steel Castings Research Committee (submitted by Professor J. H. Andrew, D.Sc.).

SUMMARY.

This paper gives a detailed report on the mechanical-test results obtained from a number of cast steels from various sources. A critical examination of the data recorded during manufacture has been made and used in conjunction with mechanical-test results in an attempt to trace the factor or factors having the most pronounced influence on the quality of cast steel.

It appears that the combined phosphorus and sulphur percentage affects the mechanical properties to a much greater extent than do other factors, such as casting temperature, &c., and the property most affected is the impact value.

Unsoundness, as indicated by blow-holes or porosity, also has a pronounced effect, particularly on the ductility properties as measured by the reduction of area and elongation. Its effect on the tensile properties depends to a large extent on the actual location of the defect in the test-piece.

There is an indication that the casting temperature, under controlled conditions, may have a slight effect on the mechanical properties. Its influence is so weak, however, that, unless the effect of other factors is completely eliminated, it is not noticed.

The microstructures of the cast steels do not differ appreciably, and give no indication of the mechanical properties to be expected. The differences in macrostructures, however, are quite distinctive, and an explanation for the variations is put forward. The macrostructure itself does not indicate what mechanical properties are to be expected from the steel.

The influence of other factors, such as the nature and distribution of inclusions, grain size and the method of manufacture, &c., has also been considered, but cannot be definitely correlated with the mechanical properties.

THE object of this investigation was to determine, as far as possible, the factor or factors which, during the various steps in the production of a steel casting, had the most decided influence on the mechanical properties of the final product.

[1] Received January 27, 1944. This paper is published by authority of the Steel Castings Research Committee. The views expressed in it are the author's, and are not necessarily endorsed by the Committee as a body.

Forty-eight test heats were made under various conditions of manufacture, each heat providing three clover-leaf test bars from which the subsequent mechanical test-pieces, micro- and macro-specimens, &c., were obtained. The form of test bar is shown in Fig. 10 and the method of cutting the test-pieces in Fig. 1. For each heat all the available data, such as the method of manufacture, melting and casting temperatures, final deoxidation additions, &c., were recorded.

The steels were tested in the as-cast, the annealed and the normalised and tempered conditions, each test being done in duplicate. Every steel was examined microscopically and photographed in all three conditions, as follows :

Fig. 1.—Clover-Leaf Test Bar; method of cutting into test-pieces.

(1) Polished; unetched.   × 50.
(2) As cast; etched.   × 50; × 500.
(3) Annealed; etched.   × 50; × 500.
(4) Normalised and tempered; etched.   × 50; × 500.

In addition, a macro-etching of the cross-section of one clover-leaf test-piece from each heat was examined and photographed. In all, 432 test-pieces were prepared and tested, 192 micro-specimens were cut and polished and 366 photographs were taken and 48 macro-etchings were prepared and photographed.

Mechanical Tests.

For convenience the results of the mechanical tests together with the data concerning the melting conditions, process, &c., are given in Table I. Included in the Table is a column indicating the condition of the test-piece. Those test-pieces which machining revealed to be unsound are indicated as being " blown "; an example is shown in Fig. 11(a). Other test-pieces were not obviously blown, but contained regions of intercrystalline porosity which were obvious only after fracture or became revealed during the pulling of the test-piece by the appearance of a very minute hole in the originally sound test-piece; these are indicated as being " porous " and are illustrated in Fig. 11(b).

Whatever the factor or factors having the most decided influence on the mechanical properties, certainly no indication can be gained by even a very close examination of Table I. Unsoundness, as indicated by either blow-holes or porosity, in many instances might quite reasonably account for the inferiority in the mechanical results as evidenced by, for example, the lower Izod and elongation values in

PLATE XVIII.

TABLE I.—*Analyses, Mechanical Test Results, Manufacturing Data, &c., for all the Steels.*

Source.	Mark.	Analysis.							As Cast.						Annealed at 920° C. for 2 hr., Furnace-Cooled.						Normalised at 880° C. for 2 hr., A.C., Tempered at 640° C. for 2 hr., A.C.						Process.	Inoculation Method.	Temperatures. °C.			Hot-Etched structure.	No. of Grains per sq. mm. at 100 diameters.
		C. %.	Si. %.	Mn. %.	S. %.	P. %.	Cr. %.	Ni. %.	Yield Point. Tons per sq. in.	Max. Stress. Tons per sq. in.	Reduction of Area. %.	Elongation on 2 in. %.	Izod Value. Ft.lb.	Condition of Tensile Test-Piece.	Yield Point. Tons per sq. in.	Max. Stress. Tons per sq. in.	Reduction of Area. %.	Elongation on 2 in. %.	Izod Value. Ft.lb.	Condition of Tensile Test-Piece.	Yield Point. Tons per sq. in.	Max. Stress. Tons per sq. in.	Reduction of Area. %.	Elongation on 2 in. %.	Izod Value. Ft.lb.	Condition of Tensile Test-Piece.			Tapped.	Ladle.	Test Bar.		
A	D1	0·20	0·21	0·80	0·025	0·02	0·07	0·10	12·0 / 16·6	29·0 / 29·9	47·0 / 50·0	33·0 / 35·0	47, 38, 25	Sound	17·9 / 17·0	29·7 / 29·8	57·0 / 57·0	38·5 / 38·0	33, 32, 33	Sound	16·8 / 16·8	30·7 / 30·6	58·0 / 54·0	38·0 / 41·0	64, 63, 64 N.B.	Sound	B.H.F.	No. 1	1670	1600	1480–1490 Optical	C	9
	D2	0·22	0·25	0·86	0·025	0·021	0·06	0·06	18·3 / 16·6	30·8 / 30·9	42·0 / 40·0	30·0 / 29·0	20, 18, 22	Sound	17·3 / 18·3	30·4 / 30·3	49·5 / 53·0	34·0 / 34·0	39, 44, 40	Sound	19·3 / 18·2	31·4 / 31·5	50·0 / 54·0	33·0 / 33·0	41, 46, 44 N.B.	Sound	B.H.F.	No. 2	1680	1640	1690 Optical	C	28
	D3	0·26	0·23	1·10	0·032	0·023	0·06	0·16	18·6 / 18·4	36·4 / 35·0	36·0 / 40·0	28·0 / 30·0	13, 16, 15	Sound	19·4 / 18·7	34·5 / 34·3	46·5 / 46·5	28·5 / 30·0	19, 19, 20	Sound	20·5 / 20·8	35·4 / 35·3	59·0 / 57·0	33·0 / 34·0	31, 30, 29	Sound	B.H.F.	No. 3	1670	1600	1610 Optical	C	2
	D4	0·25	0·38	0·93	0·03	0·02	0·14	0·04	22·0 / 20·5	37·3 / 37·2	40·0 / 28·0	26·0 / 22·0	13, 20, 18	Sound	17·2 / 17·4	33·1 / 33·8	50·0 / 47·0	30·0	27, 28, 35	Sound	18·3 / 19·0	34·9 / 34·5	52·0 / 53·0	33·5 / 32·0	29, 30, 39	Sound	A.H.F.	No. 1	1710	...	1640 Optical	C	7
	D5	0·26	0·45	1·04	0·028	0·024	0·06	Nil	19·7 / 14·6	36·3 / 36·1	26·0 / 32·0	23·0 / 24·0	11, 11, 11	Sound	20·5 / 21·5	35·2 / 35·3	49·0 / 49·0	31·0 / 31·0	43, 40, 40 N.B.	Sound	23·4 / 22·9	36·9 / 36·7	53·0 / 52·0	32·0 / 31·5	55, 58, 50 N.B.	Sound	A.H.F.	No. 2	1688	...	1640 Optical	C	52
	D6	0·26	0·42	1·00	0·027	0·016	0·04	0·03	17·1 / 20·4	35·7 / 34·9	35·0 / 35·0	24·0 / 25·0	8, 9, 12	Sound	18·8 / 18·9	34·6 / 34·6	43·0 / 46·0	30·0 / 30·0	15, 15, 15	Porous	19·2 / 20·3	34·8 / 34·9	59·0 / 53·0	32·0 / 35·0	55, 55, 32	Sound	A.H.F.	No. 3	1680	...	1485 Optical	C	2
	D7	0·27	0·23	0·92	0·009	0·017	0·08	0·30	15·3 / 14·0	32·9 / 32·8	34·0 / 37·0	26·0 / 27·0	11, 16, 12	Slightly blown / Sound	17·2 / 17·6	31·4 / 31·3	45·0 / 48·0	30·0 / 30·0	36, 36, 37	Sound	21·0 / 20·6	32·1 / 32·0	57·0 / 56·0	33·5 / 33·0	45, 47, 41	Sound	B.E.A.	No. 1	1630	1670	1450–1455 Optical	C	22
	D8	0·26	0·29	0·96	0·009	0·026	0·16	0·27	20·8 / 20·3	35·2 / 35·1	53·0 / 52·0	24·0 / 26·0	45, 47, 44	Blown in head / Sound	21·6 / 21·7	34·8 / 34·8	53·0 / 51·0	31·0 / 31·0	46, 46, 44	Sound	24·2 / 22·6	35·1 / 35·0	61·0 / 63·0	24·0 / 33·0	57, 60, 66 N.B.	Sound	B.E.A.	No. 2	1620	...	1460 Optical	B	48
	D9	0·26	0·27	0·98	0·018	0·032	0·12	0·22	12·3 / 21·4	34·3 / 31·7	16·0 / 12·0	14·0 / 7·0	7, 8, 9 M.B.	Slightly blown	18·3 / 19·5	33·6 / 33·6	27·0 / 24·0	24·0 / 23·0	8, 9, 9,	Slightly blown	19·3 / 19·5	32·6 / 32·6	40·0 / 40·0	23·0 / 25·0	55, 43, 32	Slightly blown	B.E.A.	No. 3	1610	1580	1425–1440 Optical	B	6
	DT1	0·22	0·36	0·84	0·036	0·026	0·09	0·15	18·6 / 19·0	32·4 / 32·3	42·0 / 40·0	29·0 / 28·0	16, 15, 12	Sound	20·5 / 20·5	31·2 / 31·1	50·0 / 50·0	33·5 / 33·0	32, 34, 34	Sound	20·0 / 20·0	31·7 / 31·7	56·0 / 55·0	35·0 / 34·0	38, 39, 39	Sound	A.H.F.	No. 2	...	Max. 1575 / 1640	1600 / 1500	...	S	62
	DT2	0·26	0·17	0·77	0·041	0·03	0·10	0·14	19·0 / 19·6	32·3 / 32·2	20·0 / 18·0	17·0 / 15·0	10, 12, 12	Sound	18·7 / 18·2	31·0 / 31·1	24·0 / 24·0	17·0 / 22·0	20, 20, 20	Sound	28·0 / 22·8	32·2 / 32·2	30·0 / 26·0	25·0 / 22·0	22, 24, 23	Sound / Porous	A.H.F.	No. 3	...	1640	1500	...	S	46
	DT6	0·21	0·36	0·77	0·034	0·03	0·07	0·17	18·4 / 18·0	31·8 / 31·7	25·0 / 26·0	21·0 / 25·0	15, 15, 13	Sound	17·8 / 17·8	30·8 / 30·8	38·0 / 38·0	29·0 / 29·5	29, 26, 27	Sound	21·5 / 21·6	33·3 / 33·1	37·0 / 34·0	31·0 / 24·0	33, 31, 35	Sound / Broke nr. blow-hole	A.H.F.	No. 2	...	1690+	1580	...	S	67
	DT5	0·21	0·36	0·77	0·034	0·03	0·07	0·17	18·3 / 18·0	31·9 / 31·6	30·0 / 37·0	22·0 / 22·0	18, 19, 16	Sound	18·1 / 17·8	31·0 / 30·9	42·0 / 45·0	28·0 / 30·0	29, 30, 29	Sound	19·3 / 19·4	31·7 / 31·9	42·0 / 42·0	29·0 / 30·0	34, 34, 39	Sound	A.H.F.	No. 2	...	1690+	1560	...	O	46
	DT4	0·21	0·36	0·77	0·034	0·03	0·07	0·17	17·2 / 17·7	32·3 / 32·3	35·0 / 35·0	25·0 / 25·0	18, 20, 21	Sound	18·3 / 19·0	31·2 / 31·0	48·0 / 48·0	32·0 / 31·5	30, 33, 31	Sound	19·8 / 19·8	33·0	51·0 / 46·0	33·5 / 30·0	35, 35, 38	Sound	A.H.F.	No. 2	...	1690+	1620	...	O	59
	DT3	0·21	0·36	0·77	0·034	0·03	0·07	0·17	17·7 / 17·0	31·9 / 31·8	30·0 / 32·0	20·5 / 26·0	13, 15, 15	Sound	18·5 / 18·6	31·2 / 31·2	42·0 / 42·0	32·0 / 30·5	35, 31, 32	Sound	20·0 / 21·8	32·5 / 32·5	45·0 / 45·0	31·0 / 32·0	42, 40, 36	Sound	A.H.F.	No. 2	...	1690+	1620	...	O	59
B	B7	0·215	0·33	0·87	0·024	0·018	0·12	0·41	16·9 / 17·9	33·0 / 32·1	29·0 / 25·0	25·0 / 30·0	15, 16, 15	Sound	20·4 / 19·6	31·5 / 31·5	50·0 / 50·0	31·0 / 31·0	44, 45, 44	Sound	20·8 / 20·7	32·2 / 32·3	55·0 / 52·0	30·0 / 34·0	45, 48, 46 N.B.	Sound	B.E.A. (G.E.)	No. 1	1610	1582	1480– Optical	S	45
	B8	0·25	0·28	0·81	0·024	0·026	0·12	0·36	17·0 / 17·3	34·1 / 34·1	23·0 / 15·0	21·0 / 12·0	13, 13, 13	Sound / Slightly blown	21·0 / 19·9	33·2 / 33·2	51·0 / 50·0	33·0 / 33·0	45, 42, 45	Sound	23·1 / 22·9	34·7 / 34·8	54·0 / 54·0	34·0 / 32·5	53, 45, 51 N.B.	Sound	B.E.A. (G.E.)	No. 2	1656	1625	1470 Optical	S	69
	B9	0·24	0·58	0·90	0·023	0·025	0·09	0·43	22·6 / 21·0	37·1 / 37·3	25·0 / 26·0	16·5 / 20·0	13, 17, 20	Slightly blown / Sound	19·1 / 20·7	34·7 / 34·6	52·0 / 53·0	32·0 / 30·0	26, 30, 29	Sound	21·4 / 22·5	35·1 / 35·3	54·0 / 60·0	22·0 / 32·5	42, 52, 43 N.B.	Blown in head	B.E.A. (G.E.)	No. 3	1657	...	...	S	12
	B10	0·23	0·24	0·55	0·033	0·045	0·08	0·28	16·0 / 17·0	30·7 / 30·7	36·0 / 40·0	26·0 / 30·0	10, 9, 9	Porous / Sound	16·7 / 17·1	30·9 / 31·0	46·0 / 50·0	31·5 / 31·0	26, 26, 23	Porous / Sound	18·3 / 18·3	31·9 / 31·7	52·0 / 53·0	32·0 / 32·5	30, 28, 29	Slightly blown	A.E.A.	No. 1	1630	1614	1610 Optical	S	10
	B11	0·27	0·36	0·84	0·043	0·052	0·08	0·27	23·3 / 23·2	39·6 / 39·4	13·0 / 11·0	10·0 / 10·0	7, 7, 6	Sound	22·5 / 22·5	37·8 / 37·8	25·0 / 25·0	26·0 / 22·0	31, 20, 20	Sound	25·4 / 24·1	39·3 / 39·3	25·0 / 27·0	21·0 / 22·0	18, 20, 22	Sound	A.E.A.	No. 2	1660	1610	1440 Optical	S	32
	B12	0·23	0·28	0·57	0·035	0·045	0·06	0·37	17·3 / 17·2	30·7 / 30·8	43·0 / 38·0	29·0 / 31·0	11, 13, 12	Sound	17·6 / 17·2	30·8 / 30·9	52·0 / 52·0	34·0 / 32·0	27, 27, 27	Sound	19·2 / 18·4	32·1 / 32·1	55·0 / 55·0	33·0 / 33·5	30, 32, 28	Sound	A.E.A.	No. 3	1648	1610	1440 Optical	C	14
	BO16	0·28	0·31	0·74	0·033	0·038	0·19	0·59	23·8 / 23·7	38·8 / 38·8	19·5 / 19·0	16·0 / 16·0	11, 13, 15	Sound	20·1 / 19·0	35·6 / 35·5	45·0 / 45·0	27·0 / 29·0	20, 21, 22	Sound	21·0 / 22·1	37·5 / 37·7	54·0 / 53·0	30·0 / 31·0	27, 27, 25	Sound	A.O.H.	Fe-Mn	1660	1598	...	C	6
	BO17	0·26	0·28	0·70	0·037	0·032	0·12	0·36	17·9 / 18·8	33·8 / 33·7	29·0 / 30·0	24·5 / 21·0	13, 10, 13	Sound	17·8 / 17·7	32·6 / 32·7	48·0 / 44·0	30·0 / 29·0	21, 24, 25	Sound	21·8 / 22·1	32·8 / 32·4	41·0 / 43·0	28·0 / 27·0	28, 26, 24	Sound / Slightly blown	A.O.H.	Fe-Mn	1619	...	...	S	13
	BO18	0·27	0·27	0·70	0·03	0·035	0·11	0·33	20·2 / 22·1	36·1 / 35·1	32·0 / 34·0	24·0 / 24·0	12, 18, 18	Sound	18·5 / 17·7	33·3 / 33·3	46·0 / 46·0	33·0 / 30·0	22, 21, 18	Sound	20·8 / 20·2	33·4 / 33·5	59·0 / 59·0	33·0 / 30·0	25, 23, 28	Sound	A.O.H.	Fe-Mn	1604	...	...	C	7
C	A1	0·25	0·18	0·83	0·038	0·034	0·20	Trace	19·1 / 16·7	33·9 / 34·0	16·0 / 17·0	14·0 / 16·0	8, 8, 10	Sound	18·4 / 17·4	30·7 / 31·5	26·0 / 27·0	21·0 / 23·0	10, 11, 17	Blown / Sound	20·0 / 20·1	32·3 / 32·2	33·0 / 33·0	25·0 / 21·0	25, 28, 28	Blown	B.H.F.	No. 1	1690	1655	1740 Optical	C	51
	A2	0·25	0·24	0·88	0·042	0·032	0·07	"	18·3 / 16·6	33·7 / 33·8	24·0 / 24·0	22·0 / 20·0	13, 10, 14	Sound	17·9 / 17·7	32·1 / 32·1	39·0 / 35·0	28·5 / 24·0	21, 25, 25	Sound	20·4 / 20·8	32·3 / 32·1	44·0 / 47·0	29·0 / 30·0	31, 32, 28	Slightly blown	B.H.F.	No. 2	1625	1600	1570 Optical	C	64
	A3	0·26	0·19	0·84	0·044	0·032	0·17	"	18·4 / 17·3	32·9 / 32·9	36·0 / 36·0	23·0 / 25·0	13, 12, 15	Sound	16·5 / 16·5	31·3 / 31·2	48·0 / 46·0	30·0 / 29·0	12, 13, 15	Sound / Porous	18·3 / 18·6	31·9 / 31·9	53·0 / 56·0	32·0 / 32·0	35, 35, 30	Porous	B.H.F.	No. 3	1650	1620	1450 Optical	C	6
	A3	0·26	0·19	0·84	0·046	0·032	0·088	Trace / Nil	19·4 / 19·5	33·7 / 33·9	25·0 / 26·0	20·0 / 21·0	6, 7, 7	Sound	19·0 / 18·6	33·7 / 33·8	36·0 / 36·0	26·0 / 26·0	10, 10, 11	Sound	18·9 / 18·5	34·2 / 35·0	39·0 / 39·0	27·0 / 27·0	17, 19, 20	Sound	T.C.	No. 1	1625	1585	1450 Optical	C	6
	A19	0·23	0·36	0·94	0·046	0·058	Trace	Nil	18·7 / 19·9	33·9 / 33·4	8·0 / 8·0	8·0 / 6·5	8, 8, 7,	Sound	20·1 / 20·4	33·3 / 34·3	18·0 / 24·0	12·5 / 23·0	12, 10, 13	Slightly blown / Sound	22·5 / 23·4	35·2 / 35·1	22·0 / 22·0	17·5 / 15·0	20, 20, 22	Slightly blown / Sound	T.C.	No. 2	1650	1585	1490 Optical	S	47
	A20	0·27	0·39	0·86	0·053	0·058	"	"	21·0 / 19·7	31·5 / 35·3	7·0 / 8·0	4·0 / 8·0	11, 8, 9	Slightly blown	21·1 / 20·6	35·4 / 35·5	36·0 / 36·0	18·0 / 27·0	7, 7, 9	Slightly blown	21·8 / 20·3	35·9 / 35·7	25·0 / 25·0	22·5 / 23·0	20, 16, 19	Slightly blown	T.C.	No. 3	1640	1565	1470 Optical	S	5
	A21	0·25	0·40	0·91	0·047	0·059	"	"	18·1 / 20·6	37·2 / 37·0	14·0 / 21·0	12·0 / 18·5	10, 9, 8	Slightly blown / Sound	22·7 / 22·1	36·2 / 36·0	36·0 / 37·0	27·0 / 34·0	29, 28, 28	Sound	26·0 / 25·6	37·0 / 37·4	33·0 / 34·0	18·0 / 24·0	36, 36, 34	Slightly blown / Sound	T.C.	(Ca–Si–Mn, Fe–Mn, Fe–Si and Al)	...	1560	1560	...	S	90
	EA1	0·24	0·42	1·20	0·034	0·05	...	...	16·8 / 19·0	31·7 / 31·7	35·0 / 47·0	28·5 / 31·5	9, 8, 10	Slightly blown / Sound	18·1 / 17·0	31·4 / 31·4	49·0 / 43·0	33·0 / 32·0	15, 15, 11	Blown	18·7 / 18·5	31·8 / 31·8	49·0 / 49·0	33·5 / 33·0	27, 30, 29	Blown in head	T.C.	(Ca–Si–Mn, Fe–Mn, Fe–Si)	...	1620	1620	...	S	30
	EA2	0·22	0·28	0·86	0·042	0·048	0·12	...	14·1 / 16·1	27·6 / 27·6	50·0 / 56·0	30·0 / 34·0	25, 18, 30	Sound	16·7 / 17·7	27·5 / 27·7	39·0 / 45·0	25·0 / 30·0	62, 62, 69 N.B.	Slightly blown / Sound	16·5 / 17·5	28·7 / 28·7	59·0 / 50·0	35·0 / 33·0	70, 78, 72 N.B.	Sound	T.C.	(Ca–Si–Mn, Fe–Mn, Fe–Si and Al)	...	1570	1570	...	S	35
	EA3	0·19	0·18	0·55	0·027	0·037	0·12	...	13·4 / 13·0	27·2 / 27·2	36·0 / 42·0	29·0 / 31·0	14, 13, 14	Sound	17·8 / 17·4	29·3 / 29·4	39·0 / 39·0	30·0 / 30·0	27, 29, 29	Sound	16·4 / 15·8	29·9 / 29·9	37·0 / 38·0	29·0 / 31·0	25, 25, 26	Sound	B.H.F.	No. 1	1630	1560	1580–1585 Optical	S	23
D	E1	0·18	0·29	0·83	0·04	0·023	0·45	0·05	14·7 / 17·6	30·9 / 30·9	37·0 / 37·0	27·0 / 25·0	15, 14, 14	Sound	16·9 / 17·1	29·4 / 29·4	53·0 / 53·0	34·0 / 35·0	37, 42, 37	Sound	20·3 / 20·9	30·0 / 29·9	61·0 / 58·0	37·0 / 35·0	40, 46, 38	Sound	B.H.F.	No. 2	1668	1630	1460 Optical	C	46
	E2	0·20	0·19	0·78	0·031	0·023	0·17	0·10	21·8 / 24·0	36·4 / 36·6	40·0 / 40·0	23·0 / 25·0	23, 21, 17	Sound	19·1 / 18·5	32·6 / 32·6	50·0 / 49·0	29·0 / 25·0	28, 32, 28	Sound	23·1 / 24·4	34·8 / 35·0	56·0 / 58·0	30·0 / 30·0	25, 27, 28	Sound	B.H.F.	No. 3	1480 Optical	...	1410 Optical	S	5
	E3	0·24	0·38	0·81	0·036	0·026	0·17	0·10	18·4 / 18·0	33·4 / 33·4	28·0 / 28·0	21·0 / 21·0	10, 8, 8	Sound	17·0 / 18·0	31·3 / 31·5	43·0 / 43·0	32·5 / 32·0	18, 17, 18	Sound	18·6 / 18·5	31·7 / 31·8	33·0 / 52·0	28·0 / 36·0	34, 35, 33	Slightly blown / Sound	B.E.A.	No. 1	1450 Optical	...	1580–1590 Optical	S	19
E	W1	0·25	0·279	0·86	0·013	0·031	0·093	Trace	18·2 / 18·6	31·6 / 31·6	42·0 / 45·0	28·0 / 28·0	10, 11, 12	Sound	18·6 / 19·3	31·1 / 31·0	57·0 / 55·0	35·0 / 35·0	58, 65, 65 N.B.	Sound	20·2 / 20·0	32·0 / 31·6	64·0 / 63·0	37·0 / 36·0	79, 76, 75 N.B.	Sound	B.E.A.	No. 2	1560 Optical	...	1460 Optical	S	58
	W2	0·22	0·261	0·98	0·009	0·025	Trace	"	19·8 / 18·6	27·4 / 28·5	10·0	6·0	7, 8, 8 B.B.	Badly blown	16·2 / 18·3	27·2 / 30·4	10·0 / 11·0	8·0 / 10·0	12, 12, 10 B.B.	Badly blown	18·8 / 18·0	32·5 / 27·7	20·0 / 12·0	16·0 / 10·0	37, 29, 37 B.B.	Badly blown	B.E.A.	No. 3	1540 Optical	...	1480 Optical	S	15
	W3	0·22	0·458	0·91	0·007	0·029	"	"	18·4 / 18·5	33·8 / 33·8	15·0 / 17·0	17·0 / 15·0	5, 6, 6	Sound	19·4 / 20·8	33·1 / 33·3	26·0 / 26·0	22·0 / 26·0	12, 13, 13	Sound	21·9 / 20·8	33·4 / 33·3	26·0 / 29·0	22·0 / 23·0	19, 19, 20	Small blow-holes	T.C.	No. 1	1500 Optical	...	1460 Optical	S	23
	W4	0·26	0·315	0·76	0·04	0·05	"	Nil	16·0 / 16·7	30·6 / 31·1	21·0 / 18·0	18·0 / 19·0	8, 10, 10	Sound	16·7 / 17·4	30·5 / 30·7	38·0 / 38·0	27·0 / 27·0	19, 19, 17	Sound	19·4 / 19·0	31·4 / 31·4	40·0 / 40·0	31·0 / 31·0	20, 21, 21	Sound	T.C.	No. 2	1440 Optical	...	1410 Optical	S	100
	W5	0·23	0·296	0·77	0·073	0·054	"	"	18·0 / 18·4	34·2 / 34·3	34·0 / 22·0	28·0 / 21·0	6, 7, 6	Badly blown	18·6 / 18·8	33·5 / 33·4	42·0 / 43·0	30·0 / 30·0	6, 7, 6,	Badly blown	20·5 / 20·3	33·9 / 33·8	55·0 / 55·0	35·0 / 36·0	24, 24, 26	Badly blown	T.C.	No. 3	1480 Optical	...	1450 Optical	S	17
	W6	0·24	0·373	0·85	0·045	0·06	"	"	16·0 / 16·5	33·2 / 33·3	42·0 / 39·0	32·0 / 30·0	10, 9, 10	Sound	18·3 / 18·4	32·0 / 33·0	43·0 / 43·0	32·0 / 31·5	19, 20, 17	Sound	20·3 / 20·6	34·1 / 33·9	51·0 / 52·0	30·0 / 32·0	23, 24, 24	Sound	T.C.	No. 1	1400 Optical	...	1410 Optical	S	20
F	L1	0·31	0·42	0·79	0·048	0·043	0·04	0·33	19·7 / 20·6	35·0 / 33·3	41·0 / 27·0	26·0 / 29·0	13, 13, 12	Sound	20·7 / 21·1	34·2 / 34·3	40·0 / 46·0	30·0 / 33·0	35, 24, 21	Sound	29·1 / 24·6	35·1 / 35·4	53·0 / 52·0	30·0 / 31·5	33, 32, 26	Sound	T.C.	No. 2	1540 Optical	...	1520 Optical	S	35
	L2	0·25	0·48	0·82	0·036	0·042	0·03	0·17	19·7 / 20·7	35·9 / 36·0	37·0 / 38·0	27·0 / 29·0	13, 10, 12	Sound / Porous	19·0 / 18·8	34·8 / 34·3	46·0 / 43·0	30·0 / 28·0	9, 9, 10	Sound / Porous	20·8 / 21·1	35·1 / 35·0	57·0 / 60·0	31·0 / 31·0	35, 25, 28	Sound	T.C.	No. 3	1629 (Immersion)	...	...	S	7
	L3	0·26	0·52	0·80	0·036	0·049	0·05	0·28	19·7 / 20·7	30·4 / 30·5	60·0 / 60·0	36·0 / 38·5	10, 9, 9	Sound	18·7 / 18·0	30·1 / 30·1	48·0 / 49·0	35·0 / 37·0	25, 24, 32	Sound	23·5 / 20·7	31·6 / 31·6	67·0 / 66·0	38·5 / 37·5	55, 45, 47	Sound	T.C.	No. 1	1512 Optical	...	1585	C	18
G	No. 112	0·15	0·29	0·91	0·035	0·045	0·13	0·15	16·0 / 16·5	30·3 / 30·5	40·0 / 45·0	31·0 / 32·0	10, 9, 9	Sound	19·8 / 18·3	30·4 / 30·2	49·0 / 49·0	34·0 / 33·5	37, 22, 31	Sound	22·0 / 21·4	34·1 / 32·2	60·0 / 60·0	28·0 / 34·0	28, 31, 23	Porous / Sound	T.C.	No. 2	1552 Optical	...	1579	C	52
	No. 2	0·185	0·35	1·01	0·024	0·048	0·06	0·13	15·7 / 15·9	30·3 / 30·5	40·0 / 45·0	31·0 / 32·0	9, 9, 9	Sound	18·0 / 18·3	30·0 / 30·2	56·0 / 57·0	37·0 / 37·0	48, 45, 44	Sound	21·5 / 21·0	31·5 / 31·4	65·0 / 65·0	39·0 / 38·0	48, 45, 44	Sound	T.C.	No. 3	1562 Optical	...	1603	C	13
	No. 55	0·18	0·39	0·95	0·031	0·042	0·07	0·15	17·0 / 16·0	30·1 / 30·4	57·0 / 57·0	34·0 / 34·0	8, 9, 8	Sound																			

* Broke outside gauge marks.

[1] M.B. = mildly blown. B.B. = badly blown. N.B. = not broken.

[2] B.H.F. = basic high-frequency. A.H.F. = acid high-frequency. B.E.A. (G.E.) = basic electric arc (Greaves-Etchells). A.E.A. = acid electric arc. A.O.H. = acid open-hearth. T.C. = Tropenas converter.

* C = columnar structure. S = structureless.

the as-cast condition of $W6$ compared with No. 112, or the lower reduction, elongation and Izod figures in the as-cast condition of $A21$ compared with $L3$, all of which were made by the same process and deoxidised in the same manner. It might also account for the lower elongation, 16·5%, obtained in one as-cast test-piece of $B9$ compared with 20% in the duplicate test-piece, or, to take a more glaring example, the differences in the reduction of area and elongation obtained in $B8$, the figures for duplicate results being 23% and 15% reduction and 21% and 12% elongation. Unsoundness must obviously have a pronounced effect on the mechanical properties, but is it the sole contributing factor to variations in the results? For instance, why should $B11$, an apparently sound steel, be inferior to $B9$, which shows evidence of unsoundness in the as-cast and the normalised and tempered conditions? The figures are :

		As Cast.		Annealed.		Normalised and Tempered.	
		$B9$.	$B11$.	$B9$.	$B11$.	$B9$.	$B11$.
Reduction of area.	% {	25·0	12·0	52·0	24·0	54·0	25·0
		26·0	11·0	53·0	25·0	60·0	27·0
Elongation.	% {	16·5	10·0	32·0	25·0	32·0	21·0
		20·0	10·0	30·0	22·0	33·0	22·0
Izod value. Ft.lb.	{	13, 17, 20	7, 7, 6	26, 30, 29	21, 20, 20	42, 52, 43	18, 20, 22

$B9$ and $B11$ are from the same source but made by a different process and deoxidised finally by a different method, but these factors in themselves do not account for the variations in results.

Considering the steels as a whole, without for the moment taking into consideration any variation whatever, the first and perhaps only noticeable fact is that the maximum stress seems to be the most constant measure of quality—in other words, the property which seems to be least affected by variations in the deoxidation method or process, or by the influence of any factors, whatever they might be, is the maximum stress. Although there is a range from 27·2 tons per sq. in. for $E1$ to 39·5 tons per sq. in. for $B11$, it is evident, without a detailed analysis of the figures, that the maximum stress is constant at round about 32–33 tons per sq. in. With regard to $E1$ and $B11$ it is further noticeable that, with only very few exceptions, these two steels also represent the extremes in carbon content. Included in the lowest-carbon-content group with $E1$ (carbon 0·18%) are No. 112 (carbon 0·15%) and No. 55 (carbon 0·18%), and in the highest-carbon-content group with $B11$ (carbon 0·27%) are $BO16$ (carbon 0·28%) and $L1$ (carbon 0·31%).

A graphical representation of the results as shown in Fig. 2(a) only confirms existing knowledge, $viz.$, that an increase in maximum stress is expected with an increase in carbon content. With so many factors having even only a slight effect, the nature of which cannot be definitely stated, this and subsequent curves indicate definite trends rather than any absolute relationship. When the steels are arranged according to their carbon contents the average

maximum-stress figures in Table II. are obtained.   These show a gradual increase in maximum stress with increasing carbon content.

TABLE II.—*Increase in Maximum Stress with Increase in Carbon Content.*

Group.	Carbon. %.	Number of Steels.	Max. Stress (Average). Tons per sq. in.		
			As Cast.	Annealed.	Normalised and Tempered.
A	Below 0·2	5	29·2	29·5	31·0
B	0·20–0·23	16	31·3	30·9	31·8
C	0·24–0·26	21	35·8	33·4	33·7
D	Over 0·26	6	35·6	34·0	35·3

The results for the annealed and the normalised and tempered conditions are shown graphically in Figs. 2(b) and 2(c).   Other elements like sulphur and phosphorus are not expected to affect the maximum stress so much as the reduction of area and elongation. What little effect is imparted by nickel and chromium may be annulled by the greater influence of other factors, and it is probably
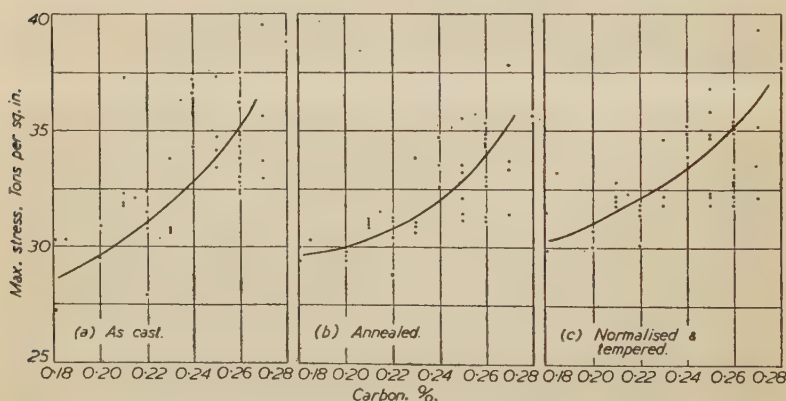
FIG. 2.—Effect of Carbon Content on the Maximum Stress.

for this reason that any attempt to determine the effect of nickel, chromium or manganese proved unsatisfactory.

The maximum stress, because of its only slight variation in value from one steel to another, which variations can be attributed quite legitimately to variations in composition only, will not give much indication of the quality of the different steels.   A better criterion of quality will probably be the impact value, the reduction of area or the elongation.

For this purpose the steels are again grouped in Table III.

Mark	As Cast Max. Stress Tons per sq. in.	As Cast Izod Calc'd	As Cast Izod Actual	As Cast Ft.lb. Diff.	Annealed Max. Stress Tons per sq. in.	Annealed Izod Calc'd	Annealed Izod Actual	Annealed Ft.lb. Diff.	Norm. & Temp. Max. Stress Tons per sq. in.	Norm. & Temp. Izod Calc'd	Norm. & Temp. Izod Actual	Norm. & Temp. Ft.lb. Diff.
Group B.—Carbon 0·20–0·23%.												
D1	29·4	15·7	37·0	+21·3	29·8	31·9	33·5	+1·6	30·7	34·1	64·0	+29·9
D2	30·9	14·9	20·0	+5·1	30·4	31·3	41·0	+9·7	31·5	33·4	44·0	+10·6
B7	52·1	14·2	15·0	+0·8	31·5	30·2	44·0	+13·8	32·3	32·6	46·0	+13·4
B10	50·7	15·0	9·0	−6·0	31·0	30·7	25·0	−5·7	31·8	33·1	29·0	−4·1
B12	50·8	14·9	12·0	−2·9	30·9	30·8	27·0	−3·8	32·2	32·7	30·0	−2·7
A19	33·8	13·3	7·0	−6·3	33·8	28·0	10·0	−18·0	34·6	30·6	19·0	−11·6
E2	30·9	14·9	14·0	−0·9	29·4	32·3	39·0	+6·7	30·0	34·7	41·0	+6·3
W2	31·5	14·5	11·0	−3·5	31·1	30·6	64·0	+33·4	31·8	33·1	77·0	+43·9
W3	28·0	16·4	8·0	−8·4	28·8	32·9	11·0	−21·9	30·1	34·6	34·0	−2·6
W5	31·0	14·8	10·0	−4·8	30·6	31·1	18·0	−13·1	31·4	33·4	21·0	−12·4
DT1	32·4	14·1	15·0	+0·9	31·2	30·5	33·0	+2·5	31·7	33·2	39·0	+5·8
DT3	31·9	14·3	15·0	+0·7	31·0	30·5	32·0	+1·5	32·8	32·2	39·0	+6·8
DT5	31·8	14·3	18·0	+3·7	31·1	30·6	29·0	−1·7	31·8	33·1	36·0	+2·9
DT4	32·3	14·1	20·0	+5·9	30·8	30·9	31·0	+0·4	32·0	32·9	36·0	+3·1
DT6	31·8	14·3	15·0	+0·7	31·4	30·3	27·0	−3·9	32·2	32·7	33·0	+0·3
EA2	31·7	14·4	9·0	−5·4	31·4	30·3	14·0	−16·3	31·8	33·1	29·0	−4·1
	Max.-Stress/Izod = 31·0 : 14·0.				Max.-stress/Izod = 30·8 : 30·7.				Max.-stress/Izod = 31·6 : 33·4.			
Group C.—Carbon 0·24–0·26%.												
D3	35·2	12·6	14·0	+1·4	34·4	21·8	19·0	−2·8	35·4	28·5	30·0	+1·5
D4	37·3	11·7	17·0	+5·3	33·5	22·4	26·0	+3·6	34·7	29·1	33·0	+3·9
D5	36·2	12·2	11·0	−1·2	35·3	21·2	41·0	+19·8	36·8	27·3	54·0	+26·7
D6	35·3	12·5	10·0	−2·5	34·6	21·7	15·0	−6·7	34·9	28·9	34·0	+5·1
D8	35·2	12·6	45·0	+32·4	34·8	21·6	45·0	+23·4	35·2	28·6	61·0	+32·4
D9	33·0	13·5	8·0	−4·5	32·6	23·0	9·0	−14·0	32·7	30·8	37·0	+6·2
B8	34·1	13·0	13·0	0	33·2	22·6	43·0	+20·4	34·8	29·0	50·0	+21·0
B9	37·2	11·7	17·0	+5·3	34·7	21·6	28·0	+6·4	35·2	28·6	46·0	+17·4
BO17	33·8	13·1	12·0	−1·1	32·7	23·0	23·0	0	32·6	30·9	26·0	−4·9
A1	34·0	13·0	9·0	−4·0	31·1	24·0	13·0	−11·0	32·3	31·1	27·0	−4·1
A2	34·8	12·7	12·0	−0·7	32·1	23·4	24·0	+0·6	32·2	31·2	29·0	−2·2
A3	32·9	13·5	13·0	−0·5	31·3	23·9	13·0	−10·9	31·9	31·5	27·0	−4·5
A21	33·4	13·3	9·0	−4·3	33·5	22·4	8·0	−14·4	25·8	38·9	18·0	−20·9
E3	36·6	12·0	20·0	+8·0	32·6	23·0	29·0	+6·0	34·9	28·9	27·0	−1·9
W1	33·3	13·3	9·0	−4·3	31·4	23·8	18·0	−5·8	31·8	31·6	34·0	+2·4
W4	33·8	13·1	6·0	−5·1	33·0	22·8	12·0	−10·8	33·4	30·2	19·0	−11·2
W6	34·3	13·4	6·0	−7·4	33·5	22·4	6·0	−16·4	33·9	29·8	25·0	−4·8
DT2	32·3	13·7	11·0	−2·7	31·1	24·0	20·0	−4·0	32·2	31·2	23·0	−8·2
L2	34·9	12·6	16·0	+3·4	34·3	21·9	23·0	+1·1	35·3	28·6	30·0	+1·4
L3	35·9	12·3	12·0	−0·3	34·8	21·6	9·0	−12·6	35·0	28·8	29·0	+0·2
EA1	37·6	11·6	9·0	−2·6	36·1	20·7	28·0	+7·3	37·2	26·9	35·0	+8·1
	Max.-Stress/Izod = 36·0 : 12·3.				Max.-stress/Izod = 33·5 : 22·3.				Max.-stress/Izod = 33·8 : 29·7.			

according to their carbon contents as indicated in Table II. In groups A and D there are so few steels that for the moment they will be ignored. In group B (carbon 0.20–0.23%) for a maximum stress of 31 tons per sq. in. an Izod value of 14 ft.lb. can quite reasonably be expected. These figures are the averages after ignoring abnormally high values or abnormally low ones due to obvious defects such as blow-holes, &c. Over this small range of composition it is reasonable to assume that the Izod figure is inversely proportional to the maximum stress. Thus, by using the ratio of the maximum stress to the Izod value given by these average figures the expected Izod value for any maximum stress can be calculated. After thus adjusting for tenacity, the Izod figure obtained on actual test for each steel will be a measure of its quality, the latter being expressed as a positive or negative value, *i.e.*, the difference between the expected and actual results. Those steels with a minus value of more than 4 are classed as inferior, those with a value between -4 and $+4$ as normal and those with a value greater than $+4$ as superior.

TABLE IV.—*Tabulation of the Steels according to their Quality based on the Differences between the Calculated and Actual Izod Values.*

Inferior steels gave Izod values 4 ft.lb. or more below the calculated value; with *normal steels* the calculated and actual values agreed to within $\pm$ 4 ft.lb.; *superior steels* gave Izod values 4 ft.lb. or more above the calculated value.

As Cast.			Annealed.			Normalised and Tempered.		
Inferior.	Normal.	Superior.	Inferior.	Normal.	Superior.	Inferior.	Normal.	Superior.
Group B.—Carbon 0·20-0·23%.								
B10	B7	D1	B10	D1	D2	B10	B12	D1
A19	B12	D2	A19	B12	B7	A19	W3	D2
W3	E2	DT4	W3	DT1	E2	W5	DT1	B7
W4	W2		W5	DT3	W2	EA2	DT3	E2
EA2	DT1		EA2	DT5			DT5	W2
	DT3			DT4			DT4	
	DT5			DT6			DT6	
	DT6							
Group C.—Carbon 0·24-0·26%.								
D9	D3	D4	D6	D3	D5	BO17	D3	D5
A21	D5	D8	D9	D4	D8	A1	D4	D6
W1	D6	B9	A1	BO17	B8	A3	A2	D8
W4	B8	E3	A3	A2	B9	A21	E3	D9
W6	BO17		A21	DT2	E3	W4	W1	B8
	A1		W1	L2	EA1	W6	L2	B9
	A2		W4			DT2	L3	EA1
	A3		W6					
	DT2		L3					
	L2							
	L3							
	EA1							

In Table IV. the steels are tabulated according to their quality. Of the ten steels classified as inferior in Table IV., seven are inferior in all conditions, *i.e.*, whether as-cast, annealed or normalised and

tempered. It appears, therefore, that the factor influencing the as-cast quality persists after heat treatment. In an attempt to determine this factor, all the steels were grouped according to their quality and all relevant data like condition of the test-piece, sulphur and phosphorus contents, casting temperature, deoxidation method, &c., were included. This revealed that all the steels with a combined sulphur and phosphorus content of over 0·09% are inferior in all conditions, and those with a lower combined sulphur and phosphorus content that are inferior show signs of unsoundness either as blow-holes or as porosity. When the steels are grouped according to their combined sulphur and phosphorus contents as in Table V. this becomes quite obvious. All the steels with a total

TABLE V.—*Quality of the Steels when Grouped according to their Combined Sulphur and Phosphorus Contents.*

In. = inferior.   N. = normal.   S. = superior.

Total Sulphur and Phosphorus.	Mark.	As Cast.	Annealed.	Normalised and Tempered.
Over 0·09%	A19	In.	In.	In.
	A21	In. (Slightly blown)	In. (Slightly blown)	In. (Slightly blown)
	W4	In.	In.	In. (Slightly blown)
	W5	In.	In.	In.
	W6	In. (Badly blown)	In. (Badly blown)	In. (Badly blown)
	EA2	In. (Blown)	In. (Blown)	In. (Blown)
0·08–0·09%	B12	N.	N.	N.
	L3	N.	In. (Porous)	N.
	EA1	N. (Slightly blown)	S.	S. (Slightly blown)
0·07–0·08%	B10	In. (Porous)	In.	In. (Slightly blown)
	A1	N.	In.	In. (Blown)
	A2	N.	N.	N. (Slightly blown)
	A3	N.	In. (Porous)	In. (Porous)
	L2	N.	N.	N.
	DT2	N.	N.	In.
0·06–0·07%	BO17	N.	N.	In. (Blown)
	E3	S.	S.	N.
	DT1	N.	N.	N.
	DT3	N.	N.	N.
	DT4	S.	N.	N.
	DT5	N.	N.	N.
	DT6	N.	N.	N. (Slightly blown)
Under 0·06%	D1	S.	N.	S.
	D2	S.	S.	S.
	D3	N.	N.	N.
	D4	S.	N.	N.
	D5	N.	S.	S.
	D6	N.	In. (Porous)	S.
	D8	S. (Slightly blown)	S.	S.
	D9	In. (Blown)	In. (Blown)	S. (Blown
	B7	N.	S.	S.
	B8	N. (Blown)	S.	S.
	B9	S. (Slightly blown)	S.	S. (Blown in head)
	W1	In.	In.	N. (Slightly blown)
	W2	N.	S.	S.
	W3	In. (Badly blown)	In. (Badly blown)	In. (Badly blown)
	E2	N.	S.	S.

sulphur and phosphorus content over 0·09% are inferior whether sound or unsound and those in the lower sulphur and phosphorus

group marked as inferior invariably show signs of unsoundness in one or more of the test-pieces. The as-cast test-piece might be marked as being sound but there might be evidence of unsoundness in one of the other test-pieces, indicating that the steel from which they were made was either blown or porous. How unsoundness will affect the mechanical results depends to some extent on its location. Some test-pieces that are blown only in the head give quite good results, whilst others with perhaps only one blow-hole
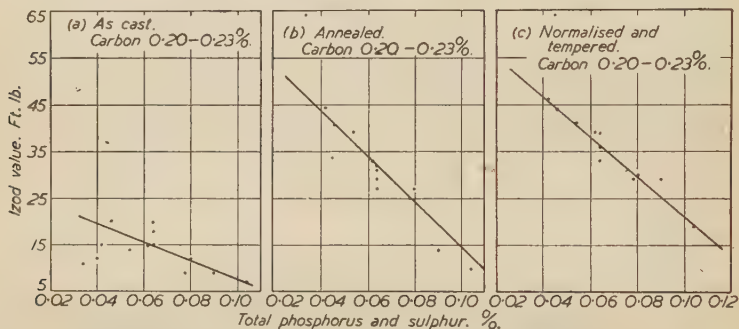
FIG. 3.—Influence of the Combined Sulphur and Phosphorus Content on the Impact Value of Steels containing 0·20–0·23% of Carbon.
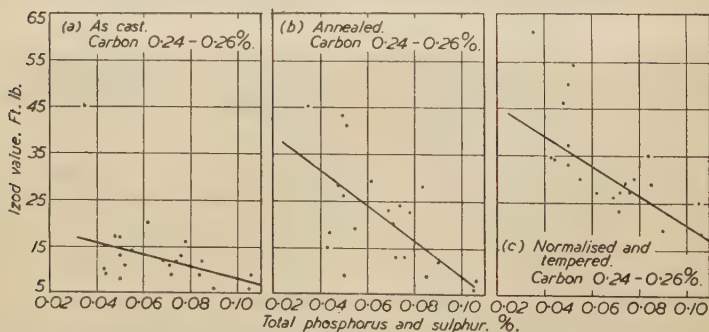
FIG. 4.—Influence of the Combined Sulphur and Phosphorus Content on the Impact Value of Steels containing 0·24–0·26% of Carbon.

in the parallel portion give a low result. This applies particularly to the elongation and reduction of area. The maximum stress is not affected to the same extent.

A graphical representation of the influence of the combined sulphur and phosphorus content on the Izod value is given in Figs. 3 and 4, where the impact values are plotted against the total sulphur and phosphorus. The steels are grouped according to their carbon content, as the influence of the sulphur and phosphorus total is then more evident than when all the steels are grouped together.

Classification of the steels according to their reduction of area or elongation gives similar results as when using the Izod value except that a larger number of steels are classed as inferior in each case. It was noted, however, that unsoundness has a much greater influence on the elongation and reduction of area. Tables and calculations are not included, as they tend to make the report unwieldy and confusing. Graphical representations of the influence of the combined sulphur and phosphorus contents are given in Fig. 5.
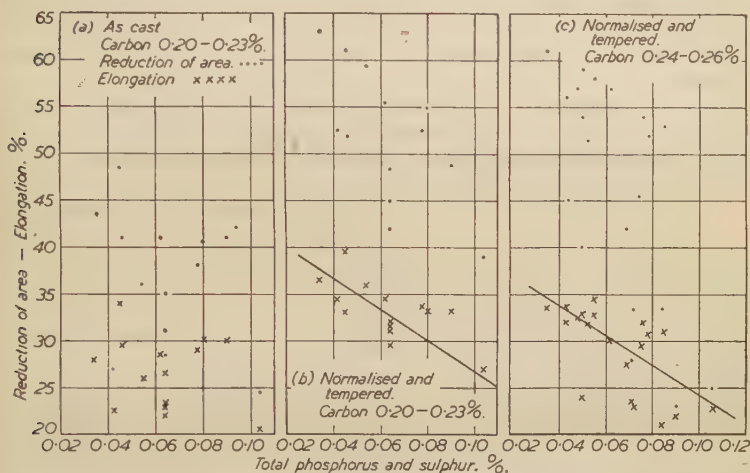
Fig. 5.—Influence of the Combined Sulphur and Phosphorus Contents on the Reduction of Area and Elongation.

The wider scattering of the points both for the elongation and for the reduction of area in Fig. 5(a) is probably due to two causes : First, there is an " as-cast " factor exerting a slight influence, which is relieved to a certain extent by annealing or normalising and tempering, probably the so-called internal stresses common to as-cast metals ; and, secondly, the stronger influence of unsoundness on the reduction of area and elongation than on the Izod value.

DEOXIDATION METHOD.

Except for a matter of about six steels, all those examined were given one of three final deoxidation treatments. These are indicated in Table I. and subsequently as deoxidation methods Nos. 1, 2 or 3 ; in method No. 1 6 oz. and in method No. 2 24 oz. of aluminium per ton were added and in method No. 3 8 oz. of calcium-silicon-manganese per ton were used. It must be pointed out that these treatments were final ladle deoxidations and were additional to the general or bath deoxidation technique as practised by each manufacturer.

To determine whether the final deoxidation method had any effect on the mechanical properties the 42 steels were divided into three groups, indicated in Table VI. as groups No. 1, No. 2 and No. 3 according to the method of deoxidation. An examination of the results for any particular test from Table I. gives the impression that the deoxidation method has no influence whatever on the mechanical properties. In any condition there are very high and very low results for the yield point, maximum stress, reduction of area, elongation and Izod value, regardless of the method used. By grouping the steels as indicated in Table VI. a comparison of the average results of the mechanical tests between each sub-group can be made.

TABLE VI.—*Average Mechanical-Test Results when the Steels are Grouped according to the Method of Deoxidation Used.*

	Grand Average.	Deoxidation Method (Averages)—		
		No. 1.	No. 2.	No. 3.
As Cast.				
Yield point. Tons per sq. in. .	18·1	17·1	18·2	19·0
Max. stress. Tons per sq. in. .	32·9	32·3	33·0	33·4
Reduction of area. % . .	31·1	33·9	29·5	30·8
Elongation. %	23·3	25·6	22·9	21·6
Izod value. Ft.lb. . . .	13·5	13·4	14·8	11·4
Annealed.				
Yield point. Tons per sq. in. .	18·7	18·1	19·3	18·6
Max. stress. Tons per sq. in. .	32·2	31·5	32·2	32·8
Reduction of area. % . .	42·9	44·1	42·7	42·0
Elongation. %	29·3	30·4	29·5	27·7
Izod value. Ft.lb. . . .	25·0	24·0	31·6	16·0
Normalised and Tempered.				
Yield point. Tons per sq. in. .	20·6	19·5	21·4	20·4
Max. stress. Tons per sq. in. .	33·1	32·4	33·3	33·6
Reduction of area. % . .	47·8	48·4	46·4	49·5
Elongation. %	30·5	31·4	30·1	30·0
Izod value. Ft.lb. . . .	35·5	35·3	38·0	31·9

The grand average is the average of the particular test for all the steels including the *BO* and *EA* series, which were not finally deoxidised by methods Nos. 1, 2 or 3.

A comparison of the figures does not enable any convincing statement to be made regarding the effect of the deoxidation method. The differences in value of any particular test, with the exception of the impact, are too small to indicate that one method is better than another, particularly in the as-cast condition; here the impact values for methods Nos. 1, 2 and 3, respectively, are 13·4, 14·8 and 11·4 ft.lb., which indicates practically no difference between methods

Nos. 1 and 2, although No. 2 can be stated to give better impact results than No. 3. In both the annealed and the normalised and tempered conditions, however, there is a definite indication that method No. 2 gives better impact values than either No. 1 or No. 3.

It is not to be expected, however, that final ladle deoxidation would have a pronounced effect on the quality of the steel. What is far more important is the general bath deoxidation technique. Additions of 6 or 24 oz. of aluminium per ton of steel will not have the same effect on a badly oxidised steel as on one that is completely deoxidised.

The behaviour of the final deoxidant will depend to a large extent on the degree of oxidation of the steel before the addition is made. There are a number of instances among the 42 casts examined where the addition of 24 oz. of aluminium per ton of steel did not produce a steel absolutely free from blow-holes, whereas some of the steels with the smaller amount of aluminium per ton are quite free from blow-holes and *vice versa*.

INCLUSIONS.

Closely allied with the deoxidation technique is the nature and deposition of the non-metallic inclusions. Every steel was examined in the as-cast condition, polished and unetched, to obtain information on the distribution of the inclusions. No attempt was made to ascertain their actual composition. Microphotographs of the unetched specimens were taken at a magnification of 50 and revealed two distinct types, *viz.*, inclusions randomly distributed and those distributed around the grain boundaries. Fig. 12 illustrates the results obtained and includes what is considered to be a typical example of numerous and few inclusions in each type of distribution. The type of inclusions found in each steel is given in Table VII.

No definite reasons for the different forms of inclusions are evident from the data provided. Both types are common to both acid and basic steels. $A1$, $A2$ and $A3$, comprising one series of casts, all show the grain-boundary type, as do $E1$, $E2$ and $E3$, all of which are basic high-frequency steels. $D1$ and $D3$, however, are also basic high-frequency steels and show the random type of inclusion distribution. On the other hand, of the nine basic electric-arc steels, in eight the distribution is definitely random, while in the other it is doubtful. In the Tropenas steels the distribution types are about equally divided.

The melting, tapping and casting temperatures also do not appear to influence the distribution. All the casting temperatures, with six exceptions, were measured with an optical pyrometer. Steels cast at temperatures from $1385°$ to $1500°$ C. have the grain-boundary type of inclusions, but quite a number of steels cast at the same temperatures show the random type. Similar remarks apply to the melting temperatures. What will determine the distribution

TABLE VII.—*Comparison of the Average Mechanical-Test Results of Steels with Randomly Distributed Inclusions with those of Steels with Grain-Boundary Inclusions.*

Average Values.	As Cast; Distribution—		Annealed; Distribution—		Normalised and Tempered; Distribution—	
	Grain-Boundary.	Random.	Grain-Boundary.	Random.	Grain-Boundary.	Random.
Yield point. Tons per sq. in. . . .	18·6	18·1	18·5	18·8	20·4	20·7
Max. stress. Tons per sq. in. . . .	33·3	33·0	36·2	32·2	33·3	33·2
Reduction of area. %	26·6	34·5	38·8	46·2	42·8	51·5
Elongation. % .	20·5	25·4	27·4	29·9	28·2	32·1
Izod value. Ft.lb. .	11·6	14·5	20·1	28·6	27·6	40·2

Grain-Boundary Distribution.

$D2$; $B10$; $B11$; $B018$; $A1$; $A2$; $A3$; $A19$; $A20$; $A21$; $W4$; $W5$; $E1$; $E2$; $E3$; $L3$.

Random Distribution.

$DT1$; $DT2$; $DT3$; $DT4$; $DT5$; $DT6$; $D1$; $D3$; $D4$; $D5$; $D6$; $D7$; $D8$; $D9$; $B7$; $B8$; $B9$; $B12$; $BO16$; $BO17$; $W1$; $W2$; $W3$; $W6$; $L1$; $L2$; 2; 112; 55; $EA1$; $EA2$; $EA3$.

of the inclusions is not the melting or casting temperature of the steel but the composition and solidification temperature of the inclusions themselves.   If they are of a low melting point they remain molten after the commencement of solidification of the steel itself, and, being the last constituent to solidify, they will be located in the grain boundaries of the steel.   The only factor which will determine the actual melting point of the inclusions is their composition, and this depends on the chemical reactions occurring in the bath of steel during manufacture and as a result of the general deoxidation technique.

An examination of the data regarding slags and general deoxidation technique failed to provide any indication of what to anticipate with regard to the nature of the inclusions in the final steel.   Actually, this is to be expected, because no data are provided with respect to the temperature of the bath when the additions of such ingredients as lime, ferro-manganese, ferro-silicon, &c., were made, or the time for which the various reactants were in contact—two only of the various factors which must have some effect on the final products of reaction.

There is no connection between the percentage of non-metallics, such as sulphur and phosphorus, elements like manganese in the final steel and the type of inclusions obtained, as the following selected examples show :

			Sulphur. %.	Phosphorus. %.	Total Sulphur and Phosphorus. %.	Inclusions.
E2	.	.	0·031	0·023	0·054	Grain-boundary
W6	.	.	0·045	0·06	0·105	Random
E3	.	.	0·036	0·026	0·062	Grain-boundary
DT1	.	.	0·036	0·026	0·062	Random

It is significant, however, that all the steels classified as inferior in all conditions in Table V. are included in the group with grain-boundary inclusions in Table VII., with the exception of EA2 and W6, both of which are badly blown. What, then, is the deciding factor—the total sulphur and phosphorus percentage or grain-boundary inclusions? Considering those steels which are sound and have grain-boundary inclusions, it is found that they give normal or superior results despite their grain-boundary inclusions. Their total sulphur and phosphorus content, however, is relatively low. It appears, therefore, that, so far as impact values are concerned, the total sulphur and phosphorus content has a greater influence than the nature of the inclusions. Similar conclusions are arrived at when the reduction of area and the elongation are considered in the same manner.

The slight effect of grain-boundary inclusions on the impact values is indicated in Fig. 6, where all specimens with randomly distributed inclusions except one have Izod values over 30 ft.lb. and all specimens with grain-boundary inclusions except three have Izod figures of less than 30 ft.lb. The influence exerted on the other mechanical properties is indicated in Table VII. It is practically negligible as regards the tensile properties. It is evident, however, that specimens with randomly distributed inclusions have a definite superiority over specimens with grain-boundary inclusions in respect of elongation and more so in respect of reduction of area and Izod value.

Effect of Various Temperatures.

The temperatures recorded by the suppliers of the steels were the tapping temperature, temperature of the steel in the ladle, casting temperature and in some cases maximum temperature reached during melting. The first three are given in Table I. Those temperatures which are not indicated as being measured optically were taken with an immersion pyrometer. Practically all the casting temperatures were taken with an optical pyrometer and cannot be considered very reliable. The variations in optical-pyrometer temperatures are considerable under the best of circumstances, and the unreliability is further aggravated by the fact that the steels came from seven different sources.

All attempts to correlate the mechanical properties with tapping temperatures, ladle temperatures or casting temperatures met with no success, and Figs. 6 and 7 show the scattering obtained. Similar types of graphs were obtained in all other cases. It is probably

true to say that the influence of other factors is far more pronounced and annuls any influence that these temperatures may have.
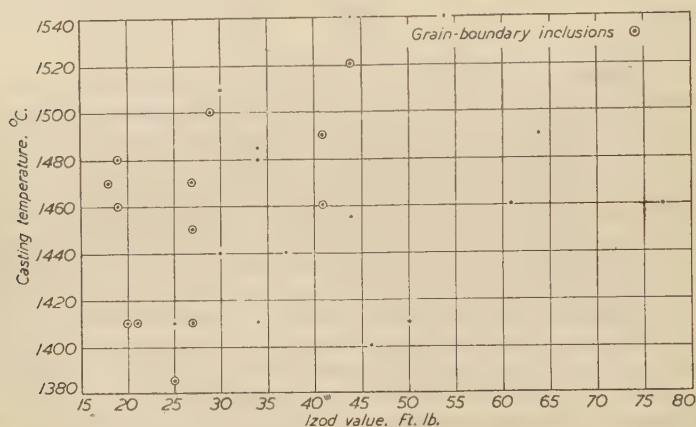
FIG. 6.—Lack of Influence of Casting Temperature on the Impact Value.
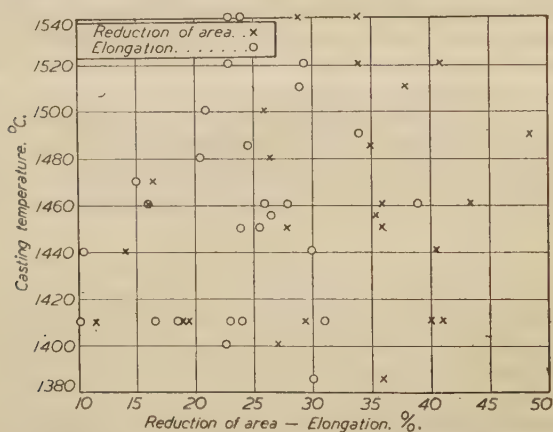
FIG. 7.—Scattering obtained when Plotting the Casting Temperature against the Reduction of Area and Elongation.

The *DT* series was specially prepared to investigate any effect that melting or casting temperature might have when the influence of other factors like the bath and final deoxidation, process of manufacture, composition, &c., is eliminated as far as possible. These six tests were obtained from three heats. One heat supplied test-pieces marked *DT*3, *DT*4, *DT*5 and *DT*6, the only variant being the casting temperature. The steel was made in an acid high-frequency

furnace and the maximum temperature recorded was a little over 1690° C. The test bars were cast from the same ladle of metal at suitable intervals, giving a range of casting temperature from 1500° to 1620° C. and the temperatures were taken with an immersion pyrometer. The results of mechanical tests are represented graphically in Fig. 8 and are repeated for clarity in Table VIII. The yield point and maximum stress do not appear to be affected
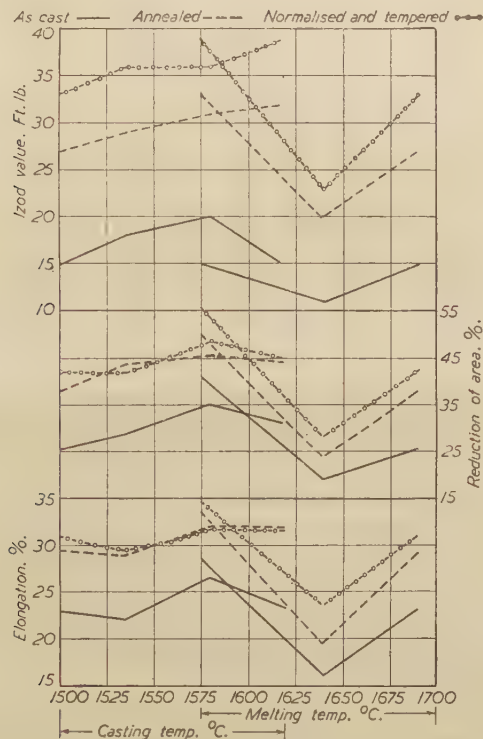
FIG. 8.—Effect of Casting Temperature and Melting Temperature on the Elongation, Reduction of Area and Izod Value.

by the casting temperature in the as-cast, the annealed or the normalised and tempered condition. The ductility, as measured by the reduction of area and elongation, is at a maximum in all conditions with a casting temperature of 1580° C. In the annealed and normalised and tempered conditions, however, the differences in the reduction of area and elongation between test bars cast at 1580° and 1620° C. are too small to be decisive. Fig. 8 seems to suggest that there is an increase in ductility with casting temperature

TABLE VIII.—*Mechanical-Test Results of Steels Cast at Various Temperatures.*

	Casting Temp. ° C.	Yield Point. Tons per sq. in.	Max. Stress. Tons per sq. in.	Reduction of Area. %.	Elonga- tion. %.	Izod Value. Ft.lb.
			As Cast.			
DT3	1620	17·4	31·9	31·0	23·3	15·0
DT4	1580	17·5	32·3	35·0	26·5	20·0
DT5	1535	18·2	31·8	28·5	22·0	18·0
DT6	1500	18·2	31·8	25·5	23·0	15·0
			Annealed.			
DT3	1620	18·6	31·2	44·0	31·3	32·0
DT4	1580	18·7	31·1	45·5	31·8	31·0
DT5	1535	18·0	31·0	43·5	29·0	29·0
DT6	1500	17·8	30·8	38·0	29·3	27·0
			Normalised and Tempered.			
DT3	1620	20·9	32·8	45·0	31·5	39·0
DT4	1580	19·8	32·0	48·5	31·8	36·0
DT5	1535	19·3	31·8	42·0	29·5	36·0
DT6	1500	21·6	32·2	38·0	27·5	33·0

up to 1580° C. and a falling off when this temperature is exceeded. It is realised that test bars cast at intermediate temperatures might upset this observation, but, although there are only four specimens, a wider casting-temperature range than that from 1500° to 1620° C. is almost impracticable.   When Fig. 8 and Fig. 7 are compared the above deductions regarding the effect of casting temperature are not true.   This is probably due to the fact that the temperatures in the latter instance were measured optically and are unreliable, or, as previously mentioned, the effect of casting temperature is far less pronounced than that of other factors and any influence on the mechanical properties is easily obliterated by the stronger influence of these other factors.

With regard to the impact values, except in the as-cast condition, the higher casting temperature gives the best results.   The increase in impact value is gradual with increasing casting temperature, and is only from 5 to 6 ft.lb. for a rise of 120° C.   The same remark also applies to the reduction of area and elongation, so that it can be safely stated that for all practical purposes, especially when the effect of other variants are not controlled, the casting temperature is not important when considering only mechanical properties.

From this same series three tests with varying melting tempera- tures were obtained, *viz.*, DT1, DT2 and DT6, with the following maximum temperatures :   DT1, 1575° C.;   DT2, 1640° C.;   DT6, 1690° C.   From Fig. 8 it is noticeable that the test results for DT2, melted at the intermediate temperature, are inferior in all conditions

and those from the steel melted at the lowest temperature, *i.e.*, *DT*1, are superior in all conditions. It is extremely unlikely, however, that this is due to the melting temperature, especially when it is pointed out that *DT*1 is the steel with the lowest combined sulphur and phosphorus content and *DT*2 that with the highest; the latter steel also gave the lowest mechanical-test results, despite its higher carbon content. Further, the only known variant to be controlled was the final deoxidation method, because steels *DT*1, *DT*2 and *DT*6 were obtained from different melts.

Grain Size.

The grain size of each steel was determined by the standard McQuaid-Ehn method, *viz.*, carburising the specimen at 927° C. for
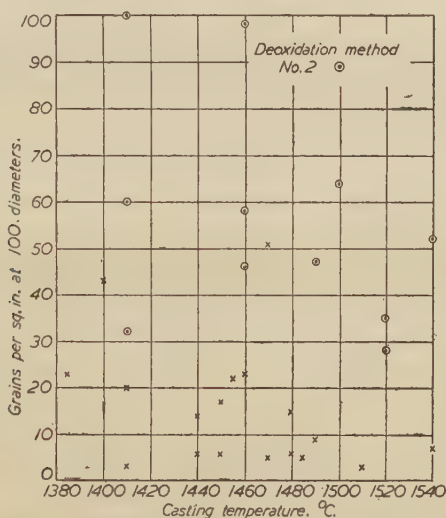
Fig. 9.—Effect of Casting Temperature and of Aluminium Additions on the Grain Size.

6 hr., polishing and etching in boiling alkaline sodium picrate. The grain size varies from as many as 100 grains per sq. in. to as few as 3 per sq. in. at a magnification of 100.

Graphs plotting the various temperatures, composition, &c., against grain size do not indicate what the important factor controlling grain size is except the aluminium addition, which is the accepted medium for grain-size control. The finer-grained steels are those which were deoxidised with 24 oz. of aluminium per ton. This is evident from Fig. 9 and Table IX., where, except in one instance, all steels deoxidised with the larger amount of aluminium

TABLE IX.—*Variation in Grain Size according to the Method of Deoxidation.*

Deoxida-tion Method.	Grains per sq. in. at 100 Diameters.	
	Actual Counts.	Average.
No. 1	9, 7, 22, 43, 10, 51, 6, 23, 19, 23, 20, 18	21
No. 2 {	28, 52, 98, 60, 32, 64, 47, 46, 58, 100, 35, 52, 62, 46, 67, 67, 46, 69	} 57
No. 3	3, 5, 6, 12, 14, 6, 5, 3, 15, 17, 7, 15	9

have over 30 grains per sq. in. at a magnification of 100. In the group deoxidised with 6 oz. of aluminium per ton only two steels, $B7$ and $A1$, have a grain size of over 30 per sq. in. No reason for these exceptions is apparent from the data provided, but it must be pointed out that in all these steels no attempt was made at grain-size control. The mere addition of aluminium, without paying attention to the general deoxidation technique, temperature, &c., does not produce a predetermined grain size.

As is indicated in the section above dealing with the deoxidation method, this grain-refining effect of aluminium has its influence on the mechanical properties, particularly on the impact value, which is evident from Table X.

TABLE X.—*Variation in Impact Values with Grain Size.*

Deoxidation Method.	Grains per sq. in. at 100 Diameters.	Average Izod Value. Ft.lb.		
		As Cast.	Annealed.	Normalised and Tempered.
No. 1	21	13·4	24·0	35·3
No. 2	57	14·8	31·6	38·0
No. 3	9	11·4	16·0	31·9

HOT-ETCHED STRUCTURE.

Cross-sections of the clover-leaf test bars were polished and etched from 20 min. in a boiling solution of 50% hydrochloric acid. Three typical examples of the resulting macrostructures are given in Fig. 13 : (*a*) A coarse columnar structure; (*b*) a fine columnar structure; and (*c*) a featureless structure. In Table I. structures (*a*) and (*b*) are designated columnar and (*c*) is called structureless.

Why steels of practically the same composition should solidify in such different and distinct patterns is not readily apparent. From what is known about the mode of solidification of steel, the final macrostructure is controlled principally by the temperature gradients

existing in the steel at the moment of commencement of solidification. A steep temperature gradient would induce a columnar structure, while a flat temperature gradient would indicate a more uniform rate of cooling from the inside to the outside of the mass of metal and hence give an equi-axed structure. The principal factors determining the temperature gradient are the conductivity of the mould material, the mass of the molten metal and the casting temperature. An alteration to any one factor can upset the influence of the other two. The influence of the casting temperature, for example, is unpredictable without a specific knowledge of the conductivity of the mould; nor does a high casting temperature necessarily mean a steep temperature gradient or a rapid non-uniform rate of cooling. For a given mass of steel, the higher the casting temperature, the greater is the quantity of heat to be absorbed and dissipated by the mould material. Moulding sands are notoriously bad conductors of heat, which, therefore, is not dissipated to the atmosphere but is accumulated in the mass of steel itself. This tends to flatten the temperature gradient and give a more uniform rate of cooling. Thus an equi-axed structure is quite possible even with a high casting temperature. With a somewhat lower casting temperature the heat may be dissipated at a sufficient rate to set up a more or less steep temperature gradient in the mass, thus producing a columnar structure. With very low casting temperatures only an equi-axed structure is possible.

The degree of coarseness of the structure, whether columnar or equi-axed, is determined by the rate of nucleus formation compared with the rate of crystal growth, the rate of nucleus formation in turn being dependent upon many factors, *e.g.*, turbulence, presence of solid matter, temperature, &c.

Table XI. indicates how far the data obtained in this investigation support these theories. There is an indication that the majority

TABLE XI.—*Types of Hot-Etched Structure obtained with Various Casting Temperatures.*

Columnar Structure.				Structureless.			
Coarse.		Fine.					
$DT3$	1620° O.*	No. 55	1603° O.*	$DT1$	1500° O.*	$B8$	1410° O.†
$DT4$	1580° O.*	No. 112	1588° O.*	$DT2$	1500° O.*	$B11$	1410° O.†
$D4$	1540° O.†	No. 2	1579° O.*	$DT6$	1500° O.*	$E3$	1410° O.†
$D5$	1540° O.†	$DT5$	1535° O.*	$L2$	1520° O.†	$W1$	1410° O.†
$D2$	1520° O.†	$A19$	1480° O.†	$W3$	1480° O.†	$W5$	1410° O.†
$D3$	1510° O.†	$A3$	1450° O.†	$A20$	1490° O.†	$L1$	1410° O.†
$A2$	1500° O.†	$D7$	1455° O.†	$A21$	1470° O.†	$B7$	1400° O.†
$D1$	1490° O.†	$BO18$	...	$D8$	1460° O.†	$E1$	1385° O.†
$D6$	1485° O.†			$W2$	1460° O.†	$B9$	...
$A1$	1470° O.†			$W4$	1460° O.†	$BO17$	...
$E2$	1460° O.†			$W6$	1450° O.†	$L3$	...
$B12$	1440° O.			$D9$	1440° O.†		
$BO16$	...						

* Immersion. † Optical.

of steels cast at temperatures above 1450° C. (optical) have a columnar structure, while at least six, also cast above 1450° C., have an equi-axed structure. No steel, however, except one, *B*12, cast below 1450° C. shows a columnar structure.

An examination of the *DT* series gives a further indication of the effect of casting temperature. Steels *DT*3, *DT*4, *DT*5 and *DT*6 are from the same melt and therefore of the same composition, melted at the same temperature, all other factors also being common to all four steels. The only variable is the casting temperature. *DT*3, *DT*4 and *DT*6 were cast at temperatures of 1620°, 1580° and 1535° C., respectively, and *DT*6 at 1500° C. *DT*6 is the only one of the four with an equi-axed macrostructure; *DT*1 and *DT*2 have structures similar to that of *DT*6 and were cast at the same temperature. In this particular instance the critical casting temperature with regard to structure is 1500° C.

If the macrostructure has any effect on the mechanical properties it must be so slight as to be readily annulled by the influence of other factors, because steels with columnar structures give exceedingly good results and also very poor results, as do also steels that are structureless.

Microstructures and Heat Treatment.

As previously indicated, micro-specimens of all the steels were obtained and examined and photographed in the as-cast, annealed, and normalised and tempered conditions. Figs. 14 and 15 are included to show the remarkable similarity in structure found in all the steels. Those illustrated are steels *E*3 and *A*3, but, except for the varying amounts of pearlite observed in some steels owing to their higher carbon contents, they can be taken as representative of any steel. In two or three instances the as-cast structure showed a more or less pronounced Widmannstätten structure, due probably to a difference in the cooling rates. The microstructures themselves, however, did not give the slightest indication of what to expect in the way of mechanical-test results.

All the steels were given two separate heat treatments, an anneal at 920° C. for 2 hr. and a normalising and tempering treatment consisting of normalising at 880° C. for 2 hr. and air-cooling followed by tempering at 640° C. for 2 hr. and air-cooling. The actual rate of heating was not observed, but it was identically the same for all the steels, which were heat-treated in the form of the clover-leaf test bar.

The results of the tests after heat treatment confirmed what was anticipated, *viz.*, a very slight improvement in the yield point and maximum stress over the as-cast results and practically no difference between the annealed and the normalised and tempered steels with regard to these two tests. It is evident from Table VI. that the impact value, reduction of area and elongation are the properties most affected by heat treatment, the elongation not being improved to the same extent as the reduction of area or the impact value. This

PLATE XIX.

FIG. 10.—Clover-Leaf Test Bar.
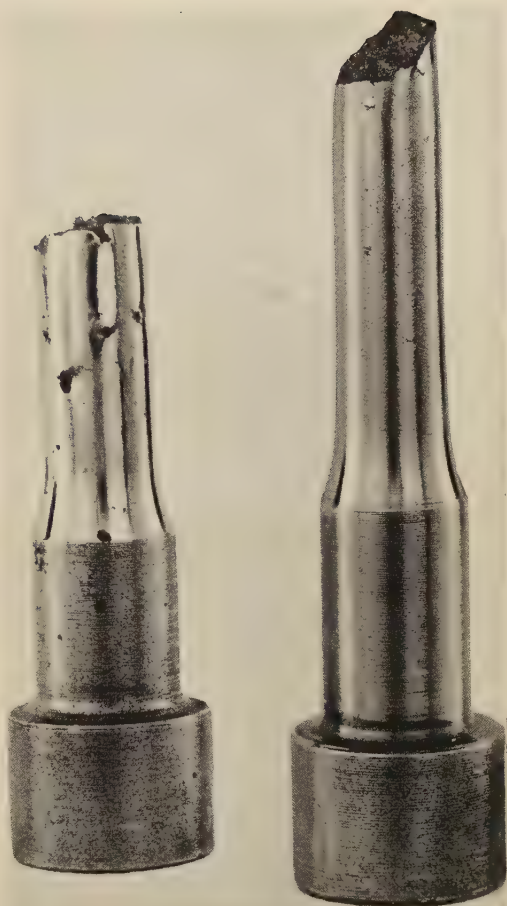
(a) Blown.   (b) Porous.

FIG. 11.—Unsound Test-Pieces. × 1½.

PLATE XX.

(a) Grain Boundary Inclusions;
numerous.

(b) Grain Boundary Inclusions; few.

(c) Random Inclusions; numerous.

(d) Random Inclusions; few.

FIG. 12.—Inclusions. × 50 (reduced to three-fifths linear in reproduction).

(a) Coarse Columnar Structure.

(b) Fine Columnar Structure.

(c) Featureless Structure.

FIG. 13.—Hot-Etched Structures of Clover-Leaf Test Bars.
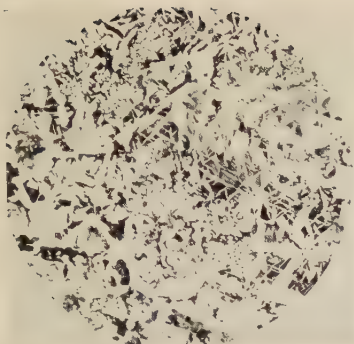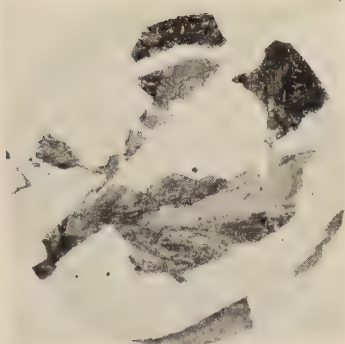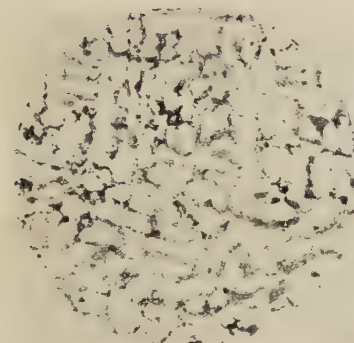
[Protheroe.

PLATE XXI.

(a) As Cast. × 50.

(b) As Cast. × 500.
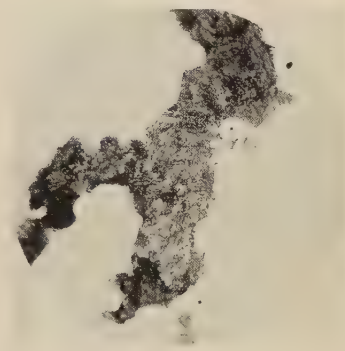
(c) Annealed. × 50.
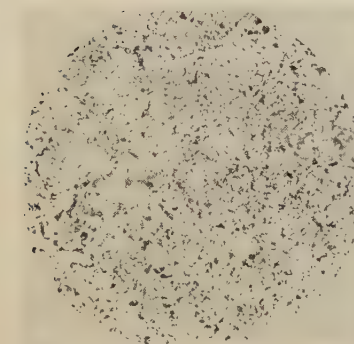
(d) Annealed. × 500.

(e) Normalised and Tempered. × 50.
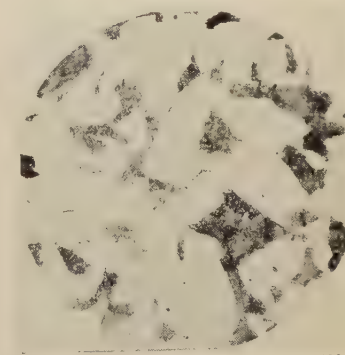
(f) Normalised and Tempered. × 500.

FIG. 14.—Microstructures of Test-Piece E3. (Reduced to two-thirds linear in reproduction.)
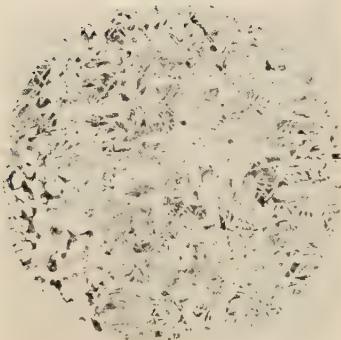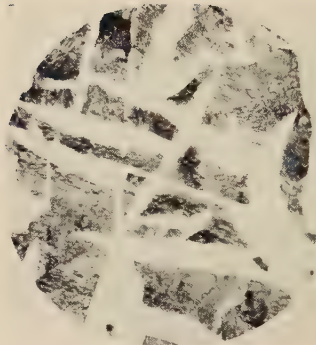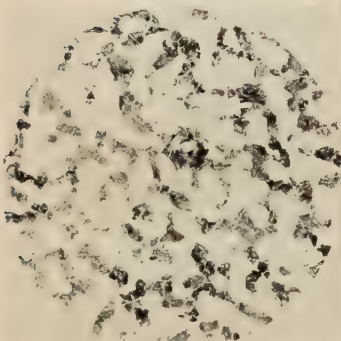
[*Protheroe.*]

PLATE XXII.

(a) As Cast.   × 50.

(b) As Cast.   × 500.
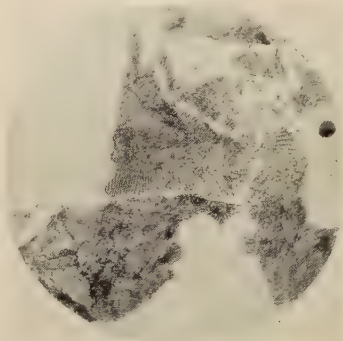
(c) Annealed.   × 50.

(d) Annealed.   × 500.
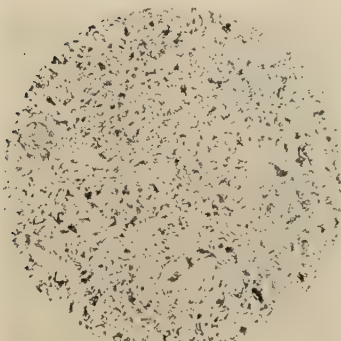
(e) Normalised and Tempered.   × 50.
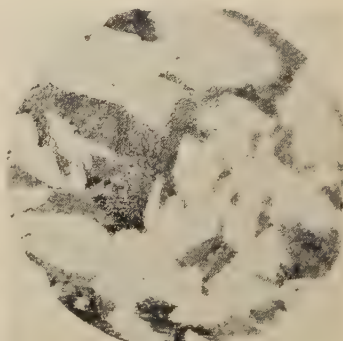
(f) Normalised and Tempered.   × 500.

FIG. 15.—Microstructures of Test-Piece *A*3.   (Reduced to two-thirds linear in reproduction.)

[*Protheroe.*

is made more evident in Table XII., where the increase in the reduction of area, elongation and Izod value on annealing and on normalising and tempering has been calculated as a percentage increase on the average figure for the corresponding as-cast result. Table XII. also indicates that the impact properties are improved by heat treatment to a much greater extent than the reduction of area or elongation, and, further, that a greater improvement in any property results from a normalising and tempering treatment.

TABLE XII.—*Increase in Mechanical-Test Results after Heat Treatment.*

	Reduction of Area.		Elongation.		Izod Value.	
		Increase.		Increase.		Increase.
As cast	31·1%	...	23·3%	...	13·5 ft.lb.	...
Annealed	42·9%	37·9%	29·3%	25·8%	25·0 ft.lb.	85·2%
Normalised and tempered	47·8%	53·7%	30·5%	30·9%	35·5 ft.lb.	163·0%

METHOD OF MANUFACTURE.

Table XIII. gives the average test results for the steels after grouping them according to the process employed in their manufacture. Nine of the steels were made by the basic high-frequency process, nine by the basic electric arc, nine by the acid high-frequency, three by the acid electric arc, three by the acid open-hearth and fifteen in the Tropenas converter.

Comparing the 18 basic steels with the 30 acid steels, there is practically no difference in the mechanical-test results except with regard to the reduction of area and impact value. The basic steels have a slight superiority only with respect to the impact strength. This applies to all conditions of the steel.

It is apparent from a close study of the test results in Table I. that, with one or two noticeable exceptions, the Izod figures for the Tropenas steels are more or less consistently low, but even so the above generalisation still holds when the results of the Tropenas steels are excluded from the acid-steel group.

Any statement regarding the relative merits of individual processes in the acid group would be at least tentative. The number of heats in two instances is only three and in the other two instances nine and fifteen. As previously mentioned, however, with only one exception, the impact values of the Tropenas steels are consistently low in the as-cast condition and even in the annealed or normalised and tempered conditions are greatly inferior to the acid high-frequency steels.

During the course of the investigation the supplier of steels *A*19, *A*20 and *A*21 intimated that the low Izod figures for these steels were due to the fact that the deoxidation methods decided upon for the purpose of the investigation were not suitable to Tropenas steels, because of their unique method of conversion from pig iron to steel.

TABLE XIII.—*Average Mechanical-Test Results for Steels Grouped according to the Steelmaking Process Used.*

Steelmaking Furnace.	As Cast.					Annealed.					Normalised and Tempered.				
	Yield Point, Tons per sq. in.	Max. Stress, Tons per sq. in.	Reduction of Area. %.	Elongation. %.	Izod Value. Ft.lb.	Yield Point, Tons per sq. in.	Max. Stress, Tons per sq. in.	Reduction of Area. %.	Elongation. %.	Izod Value. Ft.lb.	Yield Point, Tons per sq. in.	Max. Stress, Tons per sq. in.	Reduction of Area. %.	Elongation. %.	Izod Value. Ft.lb.
Average of all steels	18·1	32·9	31·1	23·3	13·5	18·7	32·2	42·9	29·3	25·0	20·6	33·1	47·8	30·5	35·5
Basic high-frequency	17·1	32·4	34·5	25·8	17·2	17·8	31·1	45·0	30·2	26·6	19·6	32·0	49·2	32·3	35·0
Basic electric arc	18·4	33·0	30·2	19·8	15·4	19·2	32·2	47·1	28·3	33·2	20·8	32·9	53·8	30·3	47·6
Average of basic steels	17·8	32·7	32·4	22·8	16·3	18·5	31·7	46·0	29·3	29·9	20·2	32·5	51·5	31·3	41·3
Acid electric arc	19·0	33·6	30·0	23·0	9·3	18·9	33·2	41·5	29·3	24·1	20·7	34·4	44·5	29·5	26·3
Acid open-hearth	21·1	36·1	27·2	20·9	13·7	18·5	33·8	36·0	29·7	21·5	21·3	34·6	50·8	30·2	26·1
Acid high-frequency	18·5	33·3	30·9	23·4	15·3	18·8	32·2	43·0	29·1	28·5	20·6	33·2	47·1	30·7	39·8
Tropenas converter	18·0	32·7	32·7	23·7	9·9	19·0	32·4	41·2	29·0	19·4	21·0	33·5	45·3	29·5	31·3
Average of acid steels	19·2	33·9	30·2	22·8	12·1	18·8	32·9	40·4	29·3	23·4	20·9	33·9	46·4	30·0	30·9
Average of acid steels excluding Tropenas converter	19·5	34·3	29·4	22·4	12·8	18·7	33·1	40·2	29·4	24·7	20·9	34·1	47·5	30·1	30·7

Steels $EA1$, $EA2$ and $EA3$ were therefore made according to the usual methods as practised in this particular works. Steels $EA1$ and $EA2$ show no improvement over the A series with regard to the Izod value, but steel $EA3$ gave an exceptionally high impact value. Table XIV. indicates the difference in deoxidation technique between steels of the A and EA series; other Tropenas steels are included for comparison. Apart from the different materials used for the deoxidation of the A and EA steels, the only notable departure from the other steels in these two series is in the case of $EA3$, for which deoxidation was carried out in the vessel and not in the ladle. That the improvement is entirely due to this fact is extremely unlikely, in view of the fact that all the other Tropenas steels were deoxidised in the vessel and gave inferior impact values.

TABLE XIV.—*Additional Data on the Deoxidation of the Tropenas Steels.*

	Silico-Man-ganese. Lb.	Calcium-Silicon-Man-ganese. Lb.	Ferro-Man-ganese Lb.	Ferro-Silicon. Lb.	Deoxidation—		Weight of Steel. Cwt.
					In—	Method.	
A19 .	23	...	23	5	Ladle	No. 1	30
A20 .	23	...	23	5	,,	No. 2	30
A21 .	23	...	23	5	,,	No. 3	30
EA1 .	...	4½	110	14	Ladle	10 lb. aluminium	60
EA2 .	...	3½	69	14	,,	...	61
EA3 .	...	4½	105	14	Converter	10 lb. aluminium	65
L1 .	37	...	...	4	Converter	No. 1	24
L2 .	39	...	...	2	,,	No. 2	26
L3 .	43	...	...	2	,,	No. 3	27
W4 .	80	...	24	14	Converter	No. 1	70
W5 .	72	...	28	14	,,	No. 2	68
W6 .	72	...	28	14	,,	No. 3	68
No. 112 .	...	...	72	21	Converter	No. 1	48+
No. 2 .	...	...	72	21	,,	No. 2	48+
No. 55 .	...	...	72	21	,,	No. 3	48+

CORRESPONDENCE.

Professor W. R. D. JONES (University College, Cardiff) wrote : Mr. Protheroe has carried out a lengthy investigation on the physical properties of cast steel of low carbon content and obtained a large amount of data the examination of which is by no means easy. Owing to the many variables the examination of the figures by statistical methods is hardly possible, but Mr. Protheroe would probably have arrived at figures which are more reliable if he had, where possible, evaluated them in accordance with these principles. This applies to those given in Tables II. and XIII. particularly, where, instead of using the arithmetic mean or common average, the weighted averages were determined.

Examination of Table I. is extremely difficult, but in spite of the large number of figures Mr. Protheroe has made a good effort to avoid being biassed and has rightly refrained from being dogmatic, as the figures do not seem to be capable of being neatly classified. This emphasises once again that steel making or melting will remain an art for some time to come ; nevertheless, the greater understanding of the underlying scientific principles will so influence the technique that the product of the steelmakers' art will be of higher quality.

There are several comments which arise from the paper. One interesting point is the almost complete absence of any reference to manganese. There are, as shown in Table I., as great, if not greater, variations in manganese content as of any of the other elements, the lowest manganese figure being 0·55% and the highest 1·2%. Good mechanical properties are obtainable from cast steels of comparatively low alloy content, provided that the manganese content is more than $\frac{3}{4}$%.

On p. 162 P Mr. Protheroe makes the interesting (if qualified) statement that there is a relationship between the maximum stress and the Izod notched-bar impact value. The notched-bar impact value cannot be judged by itself, but must be considered after taking account of the type of steel upon which the result was obtained, as the true significance of the test is still somewhat uncertain. The figures given in the paper show the advantageous effect of heat treatment on the notched-bar impact value even in the case of steels with a high total sulphur and phosphorus content. Figs. 3 and 4 show that the " inferior " steels after heat treatment give Izod values which are better than those of " superior " steels in the as-cast condition. The author's results are supported by the results of tests carried out some time ago on steel castings with 0·32% of carbon, 0·37% of silicon, 0·67% of manganese, 0·04% of sulphur and 0·024% of phosphorus, during an investigation of commercial practice in annealing steel castings, with reference particularly to the ordinary steel jobbing foundry. The notched-bar impact tests were carried out on a Charpy machine, using the Mesnager type of notch. The results were as follows :

Annealing Treatment.				Average of 4 Specimens Parallel to the Direction of Pouring.	Average of 8 Specimens Normal to the Direction of Pouring.
As cast	.	.	.	6 ft.lb.	12 ft.lb.
1 hr. at 875° C.	.	.	.	23 ,,	21 ,,
2 hr. ,,	.	.	.	26 ,,	25 ,,
4 hr. ,,	.	.	.	22 ,,	23 ,,

Mr. Protheroe has not carried out any fatigue tests on his steel castings, and it may be interesting to record that in the investigation on commercial

annealing practice the results of fatigue tests (using a Wöhler-type testing machine) were inconclusive. Many specimens failed at or below 2 million reversals even when the calculated stress was in the region of the apparent fatigue range. Specimens that withstood 2 million reversals (in this range) were found on the whole to be capable of withstanding the basic number of 10 million. It was considered that the low results given by some tests were due to intrinsic flaws present in the specimens. The bad effect of inclusions (of random distribution) will be accentuated by annealing. The data on the fatigue tests show that this is a most severe test—possibly too severe for commercial cast material which has not been forged. The chief trouble with steel castings is not the detection of more or less obvious unsoundness as given in Mr. Protheroe's paper, but the detection—often very difficult—of small areas of unsoundness (those due not only to inclusions). These often will not cause trouble in normal service. They are revealed by mechanical testing, particularly by the notched-bar impact test and the ductility figures of the tensile test. Much of the variation in steels of the same composition, such as those in the paper, may be attributed to these small hidden defects which are brought to light only by the severity of the mechanical test—*i.e.*, stress conditions much more severe than those to be expected in actual service.

Table V. is, possibly, the most significant result of this work, in that, irrespective of the many variables, it is stated (p. 163 P) that a total sulphur and phosphorus content of 0·09% will serve to classify a steel. However, a good deal depends on the mode of distribution and occurrence of the sulphur and phosphorus. The difference returned by steels B11 and B9, respectively, may be attributed to the increased sulphur and phosphorus content of the former, and if B11 (total sulphur and phosphorus 0·095%) were included in Table V. it would appear as an " inferior " steel, whereas steel B9 (total sulphur and phosphorus 0·048%) is rated in the Table as " superior." It is interesting to note that annealing caused a greater increase of the Izod value of B11 (the " inferior " steel) than of B9 (the " superior " steel). The data do not, however, warrant this being a general statement.

The microstructure of cast steel is coarse-grained and varies from a dendritic pattern to a " lattice " pattern, depending on the rate of cooling— that part of the casting which cools relatively rapidly giving the former type. The effect of annealing is to refine the grain by recrystallisation, but the dendritic pattern will persist on a macroscopical scale. Recrystallisation takes place *in situ* and has been dominated by the original dendritic pattern. The figures given in Table XII. point to the superiority of normalising and tempering over annealing, but probably the only practicable type of heat treatment of castings for general commercial purposes is annealing.

AUTHOR'S REPLY.

The AUTHOR replied : I would like to express my appreciation of Professor Jones' kind remarks and value particularly his reference to the difficulties encountered in trying to trace the individual effects of so many variables.

It is difficult to enter into a detailed discussion regarding the greater reliability of a statistical analysis with so many variables, but I have always understood that the major value of a statistical analysis lies in the fact that the effect of different variables can be eliminated in order to trace

the effect of certain others. The data are at present being examined statistically in collaboration with a colleague; the results are interesting and more or less confirm the views already put forward—it is hoped to publish them in the near future.

The results of Professor Jones' investigation on steel castings, which confirm those given in the paper, are greatly welcomed; I quite agree with his remarks regarding the unsoundness in cast steel. The defect referred to in the paper as " porosity " is that unsoundness which Professor Jones points out as being very difficult to detect—a state of unsoundness that is only revealed, as he states, "by the severity of the mechanical test." I fully agree that the impact and ductility figures are the most affected by this porosity.

Professor Jones' observations regarding steels $B9$ and $B11$ concur with my own, and $B11$ would definitely be classified as inferior if there were sufficient results available to include $B11$ in another group. It was not included in Table V., as the carbon content is above the range of Group C.

I fully agree with Professor Jones' remarks relating to the dendritic structures. Once formed, the dendritic pattern is very persistent. Annealing at very high temperatures for a considerable time did not remove it. Some of the specimens were soaked above 1200° C. for 3 hr., after which the dendritic pattern still remained. It would appear that the percentage of phosphorus and also possibly of the carbon has a controlling influence over this type of structure. This is the subject of another investigation being pursued at the present time.

TESSELLATED STRESSES.—PART III.[1]

By Dr. F. LÁSZLÓ (Engineering School, University of Melbourne, Australia).

Summary.

The characteristic component system of tessellated stresses due to crystal anisotropy is analysed for metals with cubic, hexagonal or tetragonal lattices.

The effect of tessellated stresses on thermal constants is studied. Irreversibility and hysteresis may be involved.

The question of modification, *i.e.*, reduction, of tessellated stresses and their influence on density are discussed.

Introductory Remarks.

For the sake of continuity with the previous publications on tessellated stresses, *viz.*, Parts I. and II.,[2] the numbering of equations, Tables and diagrams given in this paper are continued from those in Part II. Occasional quotations of equations (1) to (21), Tables I. to IX. and Figs. 1 to 15 are to be referred to the previous Parts I. and II. Most of the symbols used are explained in the earlier papers; the meanings of the remainder will be clear from the text.

Characteristic Stresses.

The method used in the previous investigations was based on the consideration of certain simple units of tessellation such as hollow and compound spheres, compound capped cylinders, compound cylinders and laminated slabs. Hollow and compound spheres are singularly favourable, since they are always self-compensated. The other types of compound units in random arrangement are self-compensated only if the elastic constants of their components are identical. If the latter are different, the analysis applied by equations (8) to (10) and (14) in Part II. does not account for the true stresses but only for their "characteristic" component system. Those equations provide for the continuity of strain from unit to unit, *i.e.*, at their junctions, also for the equilibrium of the random aggregate of units, but not for the continuity of stresses at the junctions of units. The latter requirement involves, even in statistical considerations, the superposition of a second coupling stress system on the characteristic one, and this is a function of, among other factors, the probability of occurrence of various arrangements of orientations of the units around a certain point of the body. It was recognised that, on metallurgical grounds, the analysis of the

characteristic stresses provided the simplest case. The super-position of the coupling stress system, however, will affect the numerical results obtained. The value a of the apparent coefficient of thermal expansion of random aggregates is primarily affected if equations (8) to (10) of Part II. are reviewed, while those of E and $1/m$ are concerned in connection with equation (14) of Part II. For the sake of simplicity and clarity, the possible influence of this superposition will not be discussed to any extent here. The absolute and relative order of magnitude of the stresses shown in Tables IV., VI. and VII. of Part II. can, however, hardly be affected, neither can the metallurgical inferences based upon them. Results obtained with equations (17) and (18) cannot be influenced in a statistical sense, since the units are self-compensated there in spite of the heterogeneous elastic properties of their components.

The above criticism has, however, hardly more than academic justification regarding the application of equations (8) and (10) in Part II. to the calculation of thermal stresses in an iron matrix with graphite, since on the one hand it is impossible to determine the correct value of a by elastic theory alone from equation (8) on account of considerable plastic yield, and, on the other hand, no noteworthy modification can be expected in the results obtained with equation (10). With small or moderate volume fractions of lamellar graphite the results yielded by equation (8) might approach theoretical correctness. The consideration of stress concentration at the edges of the graphite lamellæ involves also the effect of coupling stresses.

As to the application of equation (14), it was suggested in Part II. that the results of the calculation should be used only in connection with the gradient of the elastic stress-strain curves determined by experiment. This suggestion took into consideration the cumulative effect of all possible complications, including that of coupling stresses. The other problems previously discussed were not concerned with this question.

When a rational investigation of tessellated stresses due to crystal anisotropy is attempted, the separate consideration of the characteristic stress system is still possible. This means, first, that if, for instance, unit tension is applied to a random aggregate of crystals it can be assumed that, in the statistical mean, every crystal is subjected to the same principal strains, *viz.*, $1/E$ in the direction of the stress, and $-1/mE$ in directions at right angles to the stress, irrespective of the actual orientation of a given crystal to the direction of the external tensile stress and also of the actual size or shape of a crystal. The values of $1/E$ and $-1/mE$ are, of course, those valid for random aggregates. The system of characteristic stresses so defined for individual crystals of random aggregates is exclusively controlled by the orientation of the crystal, being characteristic of that orientation. The stresses obtained

satisfy the requirement of the continuity of strain, but not that of the stresses, at the junctions of crystals. For this reason, the correct mathematical determination of the elastic constants for random aggregates from those for single crystals cannot be done by the mere consideration of the characteristic stresses. The latter fail also to account for the " stress concentration " due to the existence of the coupling stress system. The characteristic stresses subsequently calculated include the " external " unit tension.

There is a noteworthy method,[1] which is apparently correct, for the calculation of the elastic constants of crystal aggregates from those of single crystals, and the question arises whether or not it can be modified for the analysis of tessellated stresses under conditions when the statistical units are not self-compensated. It appears, however, that regarding tessellated stresses due to crystal anisotropy, as well as in the previous case, the investigation of merely the characteristic component system suffices for many practical metallurgical engineering problems. The results will, of course, be of a qualitative character.

Tessellated stresses due to anisotropy of the linear coefficient of thermal expansion of single crystals will also be considered from the point of view of the characteristic stresses only. They are then independent not only of the actual shape of the crystal but also of its orientation. They have the same values for every crystal inside the random aggregate. The calculation is based on, among other physical constants, the linear coefficient of thermal expansion of the random aggregate. This figure must be ascertained in some other way, since it could not be determined accurately by the mere consideration of the characteristic component system of the tessellated stresses involved. Also, for this purpose, the modification of Bruggeman's method may deserve future consideration.

As was pointed out before, tessellated stresses of structural type may frequently be determined with quantitative correctness, but those due to crystal anisotropy will be analysed only for qualitative validity. Considerations as to their " qualitative " superposition do not, therefore, involve any difficulties ; it is a mere multiplication in a qualitative sense. If, however, the question of the effect of components of structural tessellation being not random aggregates but aggregates of parallel orientated crystals were to be raised, it would require investigations different from, and much more complex than, the following.

CUBIC METAL CRYSTALS.

Let a stable system of co-ordinates ξ, η, ζ be considered, such that ζ is parallel to the direction of the external unit tensile stress

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[1] D. A. G. Bruggeman, " Elastizitätskonstanten von Kristallaggregaten " (Doctor thesis presented to the University of Utrecht, Holland). The Hague, 1930 : J. B. Wolters.

which is applied to the random aggregate of crystals and ξ and η are at right angles to it; then for both the random aggregate as a whole and every single crystal the strains are invariably the same, viz. :

$$s_\zeta = \frac{1}{E}; \ s_\xi = s_\eta = -\frac{1}{mE}; \ s_{\eta\zeta} = s_{\zeta\xi} = s_{\xi\eta} = 0 \quad . \quad . \quad (22)$$

where the last equation indicates that the direct strains are principal ones, as has been mentioned above.

If the direction cosines of the crystallographical axes x, y, z of a certain crystal are, with reference to the stable system, L_x, M_x, N_x; L_y, M_y, N_y; L_z, M_z, N_z, respectively, the resolved strains of the crystals are, in the x, y, z co-ordinate system :

$$\left.\begin{aligned}
s_x &= L_x{}^2 s_\xi + M_x{}^2 s_\eta + N_x{}^2 s_\zeta; \ s_y = L_y{}^2 s_\xi + M_y{}^2 s_\eta + N_y{}^2 s_\zeta; \\
&\qquad\qquad s_z = L_z{}^2 s_\xi + M_z{}^2 s_\eta + N_z{}^2 s_\zeta \\
s_{yz} &= 2L_y L_z s_\xi + 2M_y M_z s_\eta + 2N_y N_z s_\zeta \\
s_{zx} &= 2L_z L_x s_\xi + 2M_z M_x s_\eta + 2N_z N_x s_\zeta \\
s_{xy} &= 2L_x L_y s_\xi + 2M_x M_y s_\eta + 2N_x N_y s_\zeta
\end{aligned}\right\} \quad (23)$$

The corresponding resolved stresses in the cubic crystal are to be found from either of the following two sets of equations :[1]

$$\left.\begin{aligned}
f_x &= c_{11} s_x + c_{12} s_y + c_{12} s_z \\
f_y &= c_{12} s_x + c_{11} s_y + c_{12} s_z \\
f_z &= c_{12} s_x + c_{12} s_y + c_{11} s_z \\
f_{yz} &= c_{44} s_{yz}; \ f_{zx} = c_{44} s_{zx}; \ f_{xy} = c_{44} s_{xy}
\end{aligned}\right\} \quad . \quad . \quad . \quad (24)$$

and :

$$\left.\begin{aligned}
s_x &= s_{11} f_x + s_{12} f_y + s_{12} f_z \\
s_y &= s_{12} f_x + s_{11} f_y + s_{12} f_z \\
s_z &= s_{12} f_x + s_{12} f_y + s_{11} f_z \\
s_{yz} &= s_{44} f_{yz}; \ s_{zx} = s_{44} f_{zx}; \ s_{xy} = s_{44} f_{xy}
\end{aligned}\right\} \quad . \quad . \quad . \quad (25)$$

The crystal so strained had the principal stresses f_1, f_2, f_3, decreasing algebraically, and these have direction cosines with the crystal axes x, y, z of $l_{1,2,3}$, $m_{1,2,3}$, $n_{1,2,3}$; and all of them are to be found from :

$$\left.\begin{aligned}
l_{1,2,3} f_{1,2,3} &= l_{1,2,3} f_x + m_{1,2,3} f_{xy} + n_{1,2,3} f_{zx} \\
m_{1,2,3} f_{1,2,3} &= l_{1,2,3} f_{xy} + m_{1,2,3} f_y + n_{1,2,3} f_{yz} \\
n_{1,2,3} f_{1,2,3} &= l_{1,2,3} f_{zx} + m_{1,2,3} f_{yz} + n_{1,2,3} f_z \\
l_{1,2,3}{}^2 &+ m_{1,2,3}{}^2 + n_{1,2,3}{}^2 = 1
\end{aligned}\right\} \quad . \quad . \quad (26)$$

The direction cosines of the principal stresses with the stable force system ξ, η, ζ, viz., $L_{1,2,3}$, $M_{1,2,3}$, $N_{1,2,3}$, are then obtained by means of the usual co-ordinate transformation. The share in the load taken by an individual crystal is equal to its direct stress in the ζ direction, and this, if expressed in terms of the principal stresses, becomes :

$$f_\zeta = N_1{}^2 f_1 + N_2{}^2 f_2 + N_3{}^2 f_3 \quad . \quad . \quad . \quad . \quad (27)$$

[1] E. Schmid and W. Boas, " Kristallplastizität," equations (7/1) and (7/2), and " Gruppe 9," pp. 16, 17 and 19.   Berlin, 1935 : J. Springer.

Consider Fig. 16 (a), showing an elementary cube with its centre at the common origin of the two systems of co-ordinates, the latter being coincident for this initial position. In order to find the characteristic stresses in individually orientated crystals of the random aggregate it is sufficient, for reasons of symmetry, to confine the investigation to those positions which are generated by turning the crystal around its centre such that the ζ axis intersects the top face at a rational number of points inside the triangle ABC. In order to make the ζ axis intersect this face at any point D the crystal is turned anti-clockwise first around η by ϕ, then again anti-clockwise around ξ by χ. It is, however, preferable to refer the orientation to the angles ϕ and ψ, as shown in Fig. 16 (a) and (b),
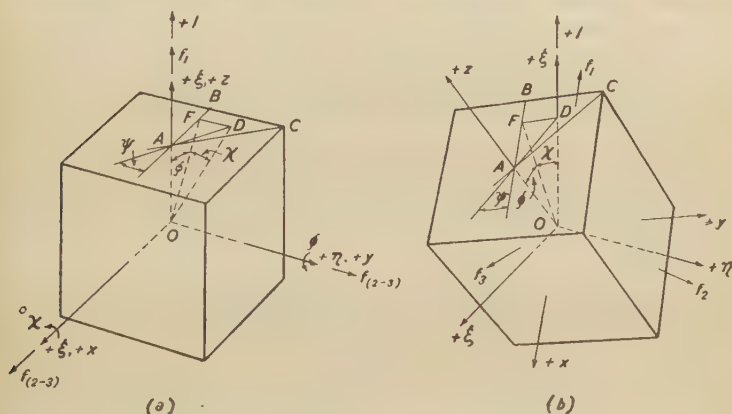
Fig. 16.—Elementary Cells in Random Aggregates of Iron Crystals subjected to Unit External Tensile Stress.

the use of which would facilitate the construction of space models if such were desired. The three angles are interdependent as follows :

$$\tan \chi = \sin \phi \tan \psi \quad . \quad . \quad . \quad . \quad . \quad . \quad (28)$$

and the direction cosines for equation (23) are :

$$\left.\begin{array}{llll} L_x = \cos \phi ; & M_x = \sin \phi \sin \chi ; & N_x = -\sin \phi \cos \chi \\ L_y = 0 ; & M_y = \cos \chi ; & N_y = \sin \chi \\ L_z = \sin \phi ; & M_z = -\cos \phi \sin \chi ; & N_z = \cos \phi \cos \chi \end{array}\right\} \quad . \quad . \quad (29)$$

α-iron crystals were investigated in 35 different positions inside the triangle ABC by varying both ϕ and ψ between 0° and 45°. The elastic constants of the single crystals s_{11}, s_{12} and s_{44} were taken from the literature,[1] and E for the random aggregate was

[1] Schmid and Boas, loc. cit., p. 200, Table 18. Here, as well as in all subsequent calculations, the respective c_{ik} coefficients were not taken from Table 3 on p. 21 of this book but calculated with " great accuracy " from the well-known equations between s_{ik},s and c_{ik},s in order to safeguard a basis for certain numerical checks on the results.

adjusted so that, with the arbitrarily chosen value $1/m = 0.3$, the volume modulus of elasticity of the random aggregate would be the same as that of a single crystal, which is expressed by :

$$\frac{3(m-2)}{mE} = 3(s_{11} + 2s_{12}) \quad . \quad . \quad . \quad . \quad (30)$$

This gives E as about 30.06×10^6 lb. per sq. in.

Equation (30) and its modification for aggregates of crystals with other than cubic lattices have been generally applied by crystal physicists in order to investigate the degree of random orientation of an aggregate. Careful correlation of existing publications on calculated [1] and experimentally determined values regarding random aggregates of cubic, hexagonal and tetragonal metals shows that equation (30) holds exactly with cubic metals but not at all with the other two types. The subsequent results indicate, furthermore, that equation (30) is satisfied by any type of aggregate of cubic crystals, and that it is probably no criterion of the degree of random orientation.

A selection of seven of the 35 sets of results for iron is shown in Table X.; as they are self-explanatory a few remarks only are necessary. It is found that the mean stress (p_m) is independent of the orientation of the crystal and is equal to that of the " external stress system," i.e., $(3p_m) = f_1 + f_2 + f_3 = 1$. This is the basis of the above inference concerning the unsuitability of equation (30) for the investigation of the degree of random orientation of cubic crystals.

The greatest yield potentials develop with those orientations for which the external force intersects two diagonally opposite edges of the elementary cube, i.e., with $\phi = 45°$ and with ψ varying from 0 to $\pm 45°$. Its maximum variation by 2.75% above the minimum, with $\phi = 45°$, is nearly negligible; further investigations suggested, however, that the difference is real, i.e., that it is not the mere consequence of an unfortunate choice of the set of values of $1/E$ and $1/m$ actually applied. When comparing the extreme values of the yield potential developing with different crystal orientations with the unit " external yield potential," a maximum increase by nearly 50% and reductions of up to about 40% are noted. The " superelasticity " displayed by the random aggregate of iron also accounts, among other things, for this " stress concentration."

The greatest characteristic stress, $f_{1,max.}$, develops with the orientation $\phi = 45°$ and $\psi = 45°$, i.e., when the body diagonal of the elementary cube is parallel to the force, it is about 30% greater than the external stress. The least yield potential is accompanied by the least value of f_1, which is about 26% less than the unit tension applied to the body as a whole.

[1] Directly by Bruggeman, loc. cit., and by others using Bruggeman's method.

TABLE X.—*Characteristic Stresses and their Orientation in Random Aggregate of Iron Crystals, for Different Orientations of Individual Crystals within the Random Aggregate and for Surface Intersections with Individual Crystals of Some Singular Orientations, due to Unit Tension Applied to the Random Aggregate.*

A selection of seven out of the thirty-five positions investigated.

Row.	Symbol of Orientation.		C00.	C30.	C33.	C36.	C60.	C63.	C66.
1	Orientation of crystal.	$\phi°$	0	22½	22½	22½	45	45	45
2		$\psi°$	0	0	22½	45	0	22½	45
3	Principal stresses.	f_1	+0·736	+0·991	+1·026	+1·130	+1·162	+1·227	+1·304
4		f_2	+0·132	+0·132	+0·100	+0·023	+0·132	+0·033	−0·152
5		f_3	+0·132	−0·123	−0·125	−0·153	−0·294	−0·260	−0·152
6	Yield potential. $f_{red}=f_1$	$-f_\xi$	0·604	1·114	1·151	1·283	1·455	1·487	1·455
7	Share in load.	f_ξ	+0·736	+0·949	+0·979	+1·251	+1·162	+1·221	+1·304
8		l_1 $\}f_1$	0	−0·555	−0·531	−0·462	−0·707	−0·662	−0·577
9		m_1	0	0	+0·244	+0·462	0	+0·351	+0·577
10		n_1	+1·0	+0·832	+0·812	+0·757	+0·707	+0·662	+0·577
11	Direction cosines of the principal stresses with the crystal axes.	l_2 $\}f_2$	0	0	+0·294	+0·707	0	+0·248	+0·408
12		m_2	+1·0	+1·0	+0·951	+0·707	+1·0	+0·936	+0·817
13		n_2	0	0	−0·094	0	0	−0·248	−0·408
14		l_3 $\}f_3$	+1·0	+0·832	+0·795	+0·535	+0·707	+0·707	+0·707
15		m_3	0	0	+0·189	−0·535	0	0	0
16		n_3	0	+0·555	+0·577	+0·654	+0·707	+0·707	+0·707
17		L_1 $\}f_1$	0	−0·195	−0·180	−0·137	0	0	0
18		M_1	0	0	−0·092	+0·119	0	+0·074	0
19		N_1	+1·0	+0·981	+0·979	+0·983	+1·0	+0·997	+1·0
20	Direction cosines of the principal stresses with the force system.	L_2 $\}f_2$	0	0	+0·236	+0·653	0	0	0
21		M_2	+1·0	+1·0	+0·971	+0·757	+1·0	+0·997	+1·0
22		N_2	0	0	−0·048	0	0	−0·074	0
23		L_3 $\}f_3$	+1·0	+0·981	+0·955	+0·745	+1·0	+1·0	+1·0
24		M_3	0	0	−0·222	−0·642	0	0	0
25		N_3	0	+0·195	+0·196	+0·182	0	0	0
26	Surface layer.	$f_{1,i}$	+0·657	+0·913	…	…	+1·083	…	…
27		$f_{2(3),i}$	+0·054	−0·202	…	…	−0·372	…	…
28		$f_{1,i}/f_1$	0·893	0·921	…	…	0·932	…	…

The figures of the extreme values for both f_1 and f_{red} compare quite tolerably with the rough estimate made by the rough considerations in Part I., *viz.*, $+35\%$ and -37%.

If the stress conditions in crystals at the free surface are examined the following consideration suggests itself for their approximate investigation. For simplicity's sake, let the surface be parallel to the plane ξ, ζ. For a surface film we have $s_\zeta = 1/E$, $s_\xi = -1/mE$, but s_η is unknown, *i.e.*, s_η is not equal to $-1/mE$. One principal stress in the surface film has to be at right angles to it and must equal zero, thus implying that its direction cosines with the crystal axes ought to be M_x, M_y, M_z. On putting into the first three of equations (26) $l = M_x$, $m = M_y$, $n = M_z$, $f = 0$, and the stresses $f_x \ldots f_{xy}$, expressed by the help of equations (23) and (24), in terms of $s_\zeta = 1/E$, $s_\xi = -1/mE$ and the unknown s_η, it is found that three distinctly different values are obtained, in general, for s_η, *i.e.*, one from each of the first three of equations (26). This indicates that the surface film warps, in general, if subjected to the strains considered, since a miraculous compensation could hardly be expected from the superposition of the coupling stress system. Thinking in terms of bulky surface crystals instead of film-like ones, one has to recognise that the crystal will bulge out in parts of its surface intersection and fall back in others. This might be ascertained in some experimental investigation, possibly by the change in reflecting power of the suitably prepared surface of a tensile test specimen, according to whether it is strained or unstrained. This peculiar behaviour of surface intersections with single crystals is apparently a phenomenon analogous with that discussed in Part II. regarding structural tessellation and illustrated diagrammatically in Fig. 12. It is, furthermore, most likely that bulging and receding develop also with structural tessellation in consequence of the strains indicated by Fig. 12.

If two crystal axes are parallel to the free surface the surface film does not display any tendency to warping, in the light of the partial analysis, with the characteristic stresses, and the first three of equations (26) are satisfied by one and the same value of s_η. The stress conditions were determined for all such singularly favourable orientations *viz.*, $C00$, $C10$, $C20$, $C30$, $C40$, $C50$ and $C60$; the results for $C00$, $C30$ and $C60$ are shown in rows 26 to 28 of Table X. It is found that the two principal stresses which are lying in the surface film, *viz.*, $f_{1,i}$ and $f_{3(2),i}$, have exactly the same orientation to the crystal axes x, y, z, and of course also to ξ, η, ζ, as the respective principal stresses f_1 and f_3 in " internal " crystals of the same orientation. Except for the orientations $C00$ and $C10$, the two principal stresses situated in the surface layer, *viz.*, $f_{1,i}$ and $f_{2(3),i}$, have opposite signs. It is seen that for the orientations $C20$ to $C60$ the yield potential is not relieved in surface intersections at all, *i.e.*, $f_{red,i} = f_{1,i} - f_{2(3),i} = f_{red} = f_1 - f_3$. With the intersections $C00$ and $C10$, some increase in the yield potential is noticed, since

$f_{red,i} = f_{1,i}$; however, also for these intersections $f_{1,i} - f_{2(3),i} = f_1 - f_3$. This observation is characteristic of all cubic metals, as is seen in Table XI.

Some relaxation is noticed with the maximum stress $f_{1,i}$ in the intersections, as shown in row 28 of Table X. by the factor $f_{1,i}/f_1$; it is, however, less than 7% for large values of f_1, e.g., that for $C60$.

Noteworthy stress relaxation is found on considering the mean stress (p_m) or more conveniently on comparing the value of $(3p_m) = 1$ in the interior for any orientation with that in intersections $(3p_{m,i}) = f_{1,i} + f_{2(3),i}$, the latter being invariably 0·711 for all the " singularly favourable " orientations. This relaxation is, however, of no benefit whatever in regard to the load capacity of the surface film. The value of 0·711 for iron is very close to that of $(m - 1)/m$ which was found to account for the relaxation of structural tessellated stresses of cementite or austenite or martensite with iron. The figure 0·711 is, however, the result of mere chance and has nothing to do with $(m - 1)/m$ for iron. Tungsten is a cubic metal too, and its single crystals show practically no elastic anisotropy. Poisson's ratio for random aggregates of tungsten crystals amounts to $1/m = 0·2$, which involves $(m - 1)/m = 0·8$ for tungsten aggregates. It is found, however, with tungsten surface films that $(3p_{m,i})$ is practically equal to $(3p_m)$, i.e., no relaxation takes place at all.

The magnitude of this index of " theoretical " relaxation is invariable for one and the same metal over the " favourable " orientations, as shown for different cubic metals in Table XI. : its numerical value is, however, characteristic of a given metal.

Of cubic metals, the elastic constants of sodium, potassium, aluminium, copper, a brass containing 72% copper plus 28% zinc, silver and gold are available.[1] Sodium and potassium are body-centred like α-iron, while the others are face-centred. As Table XI. indicates, the calculation was again based on the measured values of s_{11}, s_{12} and s_{44}, and on selected values of E. Bender calculated E for sodium and potassium by Bruggeman's method. His results have been given in pound units in Table XI. For the face-centred metals, E was fixed on the basis of the most reliable publications of measured values; $1/m$ was then calculated for all metals from equation (30). The principal stresses and the yield potentials were determined for three orientations of internal crystals, viz., $C00$, $C60$ and $C66$; since the yield potentials for $C60$ and $C66$ are identical the value is shown for $C66$ only, in row 21. The characteristic stresses in surface intersections were investigated for $C00$ and $C60$ only. While the effects of intersection on f_{red} and on $(3p_{m,i})$ have been quoted above, it should be added that the relaxation of the maximum stress, viz., $f_{1,i}/f_1$ as shown in rows 11 and 18 of Table XI. varies markedly with the different metals; it is, however, much less

[1] Schmid and Boas, loc. cit., p. 200, Table 18. For sodium and potassium, see O. Bender, Annalen der Physik, 1939, vol. 34, p. 359.

TABLE XI.—*Characteristic Stresses in Random Aggregates of Cubic Metal Crystals, for Three Singular Orientations and Surface Intersections of Two of them, due to Unit Tension Applied to the Random Aggregate.*

Elastic constants:
s_{11}, s_{12}, s_{44} — 10^{-13} sq. cm. per dyne.
E — 10^{6} lb. per sq. in.
$1/m$

$f_2 = f_3$, $f_1 = f_x$
$f_{red} = f_1 - f_3$
$f_{1,i}$, $f_{3,i}$, $f_{1,i}/f_1$, $f_{1,i}/f_3$
$(3p_{m},\lambda)_{00} = (f_{1,i} + f_{3,i})_{00} / (f_{1,i} + f_{3,i})_{00} =$
$f_2 = f_1$, $f_3 = f_y$
$f_{3,i}$, $f_{1,i}/f_1$, $f_{3,i}/f_3$
$f_{red} = f_1 - f_3$

Principal stresses in— { Interior ; Surface layer }

Principal stresses in— { Interior ; Surface layer ; Principal stresses in interior }

Row.	Orientation.	Material :	Iron.	Sodium.	Potassium.	Aluminium.	Copper.	Brass; 72% Copper, 28% Zinc.	Silver.	Gold.
1	$C00$ $\phi = 0°$ $\psi = 0°$	s_{11}	+7·57	+420·0	+823·0	+15·9	+15·0	+19·4	+23·2	+24·5
2		s_{12}	−2·82	−190·0	−370·0	−5·8	−6·3	−8·35	−9·93	−11·3
3		s_{44}	+8·62	+162·0	+380·0	+35·16	+13·3	+13·9	+22·9	+25·0
4		E	30·06	1·298	0·513	10·0	17·0	14·5	11·0	11·25
5		$1/m$	0·3	0·321	0·353	0·352	0·359	0·365	0·373	0·426
6		$f_1 = f_x$	+0·736	+0·495	+0·547	+0·936	+0·696	+0·661	+0·698	+0·676
7		$f_2 = f_3 = f_y$	+0·132	+0·253	+0·227	−0·032	+0·152	+0·169	+1·151	+0·162
8		$f_{red} = f_1 - f_3$	+0·604	0·242	+0·320	+0·903	+0·544	+0·492	−0·547	+0·514
9		$f_{1,i}$	+0·657	+0·286	+0·362	+0·917	+0·586	+0·533	+0·585	+0·537
10		$f_{3,i}$	+0·054	+0·044	+0·042	+0·014	+0·042	+0·041	+0·038	+0·023
11		$f_{1,i}/f_1$	+0·593	0·578	+0·662	+0·980	0·842	0·807	0·838	0·795
12		$f_{1,i}/f_3$	+0·711	+0·330	+0·403	+0·931	+0·628	+0·575	+0·623	+0·560
13	$C60$ $\phi = 45°$ $\psi = 0°$	$f_2 = f_1$	+1·162	+1·285	+1·393	+1·042	+1·296	+1·398	+1·215	+1·154
14		$f_3 = f_y$	+0·132	+0·253	+0·227	+0·032	+0·152	+0·169	+0·151	+0·162
15		$f_{3,i}$	+0·294	−0·537	−0·619	−0·074	−0·448	−0·567	−0·366	−0·317
16		$f_{1,i}/f_1$	+1·083	+1·076	+1·208	+1·023	+1·186	+1·270	+1·102	+1·016
17		$f_{3,i}/f_3$	−0·372	−0·746	−0·804	−0·092	−0·558	−0·695	−0·479	−0·455
18		$f_{red} = f_1 - f_3$	0·932	0·838	0·867	0·982	0·915	0·908	0·907	0·880
19	$C66$ $\phi = 45°$ $\psi = 45°$	$f_2 = f_1$	+1·304	+1·548	+1·674	+1·077	+1·496	+1·643	+1·376	+1·314
20		$f_3 = f_y$	+0·152	−0·274	−0·337	−0·038	−0·248	−0·322	−0·188	+0·157
21		$red = f_1 - f_3$	1·455	1·822	2·012	1·115	1·744	1·965	1·564	1·471

for large values of f_1 than for orientations like $C00$. Since its value does not exceed 10% with the orientation $C60$ in engineering metals and since the superimposed effect of the coupling stress system is unknown, it appears advisable to consider tessellated stresses due to crystal anisotropy of cubic metals as not being relieved at all at surface intersections, having regard to the load capacity of the surface layer.

The yield of random aggregates of cubic metals is in general considerably enhanced by the increase, more or less, in yield potential, owing to the characteristic stresses due to crystal anisotropy ; the random arrangement is, however, accompanied by such an increase in the yield resistance that the latter greatly over-compensates the former. The random arrangement does not seem to be open to criticism in this respect.

If aggregates of cubic crystals are subjected to body tension and exposed to service conditions which may facilitate the development of selective corrosion of the surface layer, the question of random *versus* parallel orientation appears in a different light. Regarding the critical figures of f_1 in row 19 of Table XI., aluminium appears the most favourable ; it resists selective corrosion very well indeed in its pure state, but this feature may be attributed exclusively to the quality of the surface oxide film. Brass would not seem very much inferior to copper in the light of $f_{1,max.}$; their performance is, however, extraordinarily different in regard to grain-boundary corrosion under numerous kinds of service conditions in engineering practice. It is also noteworthy that $f_{1,max.}$ of iron is even less than those of the more or less noble metals gold and silver. It should therefore be emphasised that the actual existence of any great degree of elastic anisotropy would not account for a direct danger of selective corrosion of random aggregates. If service conditions are suitable for selective corrosion, the random feature reduces the permissible limit of the body tension about proportionally to $1/f_{1,max.}$.

The above consideration adds further justification to the suggestion made in Part I. as to the advisability of the study of the performance of parallel-orientated aggregates. The fact that random orientation is a vital necessity in some cases, as, for instance, in certain rotating machine components, should not lessen the interest in such investigations ; neither should the inevitable ear formation in deep-drawing arising from increasing parallel orientation cause the use of parallel-orientated sheet metal for deep-drawing to be forbidden for this reason only. Some progress should result, even as regards practice.

HEXAGONAL METAL CRYSTALS.

For hexagonal metal crystals equations (24) and (25) are to be replaced by the following ones :[1]

[1] Schmid and Boas, *loc. cit.*, " Gruppe 6," p. 18, and statement concerning $s_{66} = 2(s_{11} - s_{12})$, p. 19.

$$\left.\begin{array}{l} f_x = c_{11}s_x + c_{12}s_y + c_{13}s_z \\ f_y = c_{12}s_x + c_{11}s_y + c_{13}s_z \\ f_z = c_{13}s_x + c_{13}s_y + c_{33}s_z \\ f_{yz} = c_{44}s_{yz}; \ f_{zx} = c_{44}s_{zx}; \ f_{xy} = \tfrac{1}{2}(c_{11} - c_{12})s_{xy} \end{array}\right\} \quad . \quad . \quad . \quad (31)$$

and :

$$\left.\begin{array}{l} s_x = s_{11}f_x + s_{12}f_y + s_{13}f_z \\ s_y = s_{12}f_x + s_{11}f_y + s_{13}f_z \\ s_z = s_{13}f_x + s_{13}f_y + s_{33}f_z \\ s_{yz} = s_{44}f_{yz}; \ s_{zx} = s_{44}f_{zx}; \ s_{xy} = 2(s_{11} - s_{12})f_{xy} \end{array}\right\} \quad . \quad . \quad . \quad (32)$$
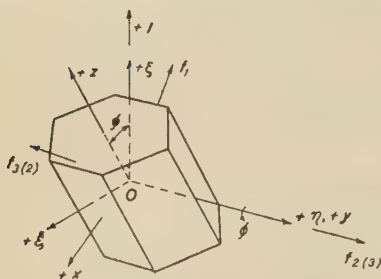
FIG. 17.—Elementary Cell in a Random Aggregate of Zinc Crystals subjected to Unit External Tensile Stress.

The anisotropy of hexagonal crystals is rotationally symmetrical. The characteristic stresses are therefore exclusively controlled by the angle ϕ (see Fig. 17) made by the hexagonal axis z with the direction ζ of the unit external tension, as far as the interior of the body is concerned. The calculation is simplified if the y axis of the crystal is always assumed parallel to the stable η axis of the force system. Then equation (29) is to be replaced by :

$$\left.\begin{array}{l} L_x = \cos \phi; \ M_x = 0; \ N_x = -\sin \phi \\ L_y = 0; \quad\quad M_y = 1; \ N_y = 0 \\ L_z = \sin \phi; \ M_z = 0; \ N_z = \cos \phi \end{array}\right\} \quad . \quad . \quad . \quad (33)$$

Since zinc was quoted in Part I. and it is the most used of the hexagonal metals, the characteristic stresses of its random aggregate were completely analysed for 13 different orientations, viz., from $\phi = 0$ to $\phi = 90°$ in steps of $7\tfrac{1}{2}°$. The elastic constants [1] of the single crystals, viz., s_{11}, s_{12}, s_{13}, s_{33}, s_{44}, are shown in Table XIV., and also those for the random aggregate, the latter having been calculated by Bruggeman's method.[2] The principal stresses and their orientations are again obtained from equation (26), and the direction cosines with the force system by a further co-ordinate transformation.

The results (for seven of the 13 orientations) are shown in Table XII. As the stress $f_{2(3)}$ is invariably parallel to the η and y axes, its direction cosines are not quoted, the two other principal stresses, viz., f_1 and $f_{3(2)}$ are always at right angles to both η and y. It is noteworthy how large is the variation with ϕ of the values of the mean stress as indicated by the figures for $(3p_m)$. This shows that the volume elasticity of hexagonal crystals is a very sensitive function of the actual stress conditions, i.e., of the feature of the

[1] Schmid and Boas, loc. cit., p. 200, Table 18.

[2] W. Boas, Schweizer Archiv für angewandte Wissenschaft und Technik, 1935, vol. 1, p. 257, Table 2.

TABLE XII.—*Characteristic Stresses and their Orientation in Random Aggregates of Zinc Crystals, for Different Orientations of Individual Crystals, due to Unit Tension Applied to the Random Aggregate.*

A selection of seven out of the thirteen positions investigated.

Row.	Symbol of Orientation :	H0.	H2.	H4.	H6.	H8.	H10.	H12.
1	Orientation of crystal. $\phi°$	0	15	30	45	60	75	90
2	Principal stresses $\left\{ f_1 \right.$	+0·376	+0·516	+0·780	+1·049	+1·266	+1·402	+1·447
3	$\left\{ f_{2(3)} \right.$	+0·047	+0·026	−0·032	−0·111	−0·189	−0·247	−0·268
4	$\left\{ f_{3(2)} \right.$	+0·047	−0·009	−0·043	+0·002	+0·099	+0·193	+0·232
5	Yield potential. $\quad f_{red} = f_1 - f_{min.}$	0·329	0·525	0·824	1·160	1·456	1·649	1·715
6	Mean stress. $\quad (3p_m) = f_1 + f_{2(3)} + f_{3(2)}$	+0·471	+0·534	+0·706	+0·941	+1·176	+1·348	+1·411
7	Share in load. $\qquad f_s$	+0·376	+0·470	+0·710	+1·000	+1·246	+1·397	+1·447
8	Direction cosines $\Big\{$ Crystal $\big\{ l_1 = -n_{3(2)}$	0	−0·534	−0·731	−0·844	−0·925	−0·980	−1·0
9	of the principal $\Big\{$ axes $\big\{ n_1 = l_{3(2)}$	+1·0	+0·845	+0·682	+0·537	+0·381	+0·200	0
10	stresses with $\Big\{$ Force $\big\{ L_1 = -N_{3(2)}$	0	−0·297	−0·291	−0·217	−0·133	−0·060	0
11	the— $\Big\{$ system $\big\{ N_1 = L_{3(2)}$	+1·0	+0·955	+0·956	+0·976	+0·991	+0·998	+1·0

actual set of three principal stresses, and is not simply controlled by the mean stress as with cubic crystals. The same holds also for the tetragonal β tin. In fact there is hardly any point in quoting the values of $(3p_m)$ and $(3p_{m,i})$ in Tables XII. to XIV.; this has been done only to emphasise the extreme dependence of $(3p_m)$ on ϕ.

The characteristic stresses were calculated also for surface intersections of two convenient orientations, *viz.*, $H0$ and $H12$, which comply with the requirement for simple mathematical analysis of two crystal axes being parallel to the surface of the orientation ξ, ζ. For intersections with $H0$, the crystal axis y is taken parallel to η, *i.e.*, at right angles to the free surface; this results in $f_{y,i} = 0$. For intersections with $H12$ two different arrangements of the crystal may ensure that two crystal axes would be parallel to the free surface, *viz.*, the z axis of the crystal may make an angle of $\theta = 0$ with the normal η to the free surface when $f_{z,i}$ would be zero, or it may make angles of $\theta = \phi = 90°$ with ζ and η when $f_{y,ii}$ would be zero. All the figures for these two variations with $H12$ are marked with different suffixes as " i " and " ii," respectively. Furthermore, since the principal stresses of the characteristic system for $H0$ and $H12$ together with those of the respective intersections are invariably parallel to certain crystal axes, all stresses are marked in Table XIV. with the suffixes for the crystal axes.

This Table includes also the significant characteristic stresses of internal and surface crystals of the orientations $H0$ and $H12$ for random aggregates of cadmium, magnesium and β tin. The elastic constants for the latter metals were taken from the same sources as were quoted for zinc. According to the arrangement made for the y crystal axis for the hexagonal metals, $f_{yz} = f_{xy} = 0$ for all crystal positions concerned. If the same procedure of calculation is applied to a tetragonal metal, s_{66} or c_{66} does not appear in the mathematical operations at all, hence the " hexagonal " method was used for the investigation of random aggregates of tin. Elastic constants for the latter have not been calculated by Bruggeman's method yet; so-called observed values were therefore used. Tables XIII. and XIV. give the results obtained for cadmium, magnesium and tin (in Table XIII. only seven of the 13 orientations investigated are recorded).

Since the results are so self-explanatory, and the above considerations regarding cubic metals further facilitate their study, only a few special remarks will be made. The numerical values of both f_1 and f_ζ for tin over the whole range from $\phi = 0$ to $\phi = 90°$ are invariably greater than the unit average tensile stress applied to the random aggregate. Owing to the coupling stress system not having been considered, the space integral of the f_ζ values should not be expected to maintain exact equilibrium with the external unit tension with any one of the cubic or hexagonal (and tetragonal) metals. The discrepancy with tin appears, however, to be rather

TABLE XIII.—*Characteristic Stresses in Random Aggregates of Hexagonal (and Tetragonal) Metal Crystals, for Different Orientations of Individual Crystals, due to Unit Tension Applied to the Random Aggregate.*

A selection of seven out of the thirteen positions investigated.

Row.	Symbol of Orientation: Orientation of Crystal. $\phi°$:	H0. 0.	H2. 15.	H4. 30.	H6. 45.	H8. 60.	H10. 75.	H12. 90.
	Cadmium.							
1	Principal stresses. $\begin{cases} f_1 \\ f_{3}(=f_y) \\ f_2 \end{cases}$	$+0{\cdot}369$	$+0{\cdot}440$	$+0{\cdot}640$	$+0{\cdot}922$	$+1{\cdot}211$	$+1{\cdot}424$	$+1{\cdot}502$
2		$-0{\cdot}191$	$-0{\cdot}186$	$\pm0{\cdot}170$	$-0{\cdot}148$	$-0{\cdot}126$	$-0{\cdot}110$	$-0{\cdot}104$
3		$-0{\cdot}191$	$-0{\cdot}159$	$-0{\cdot}078$	$+0{\cdot}024$	$+0{\cdot}119$	$+0{\cdot}187$	$+0{\cdot}211$
4	Yield potential. $f_{red} = f_1 - f_3$	$0{\cdot}561$	$0{\cdot}626$	$0{\cdot}809$	$1{\cdot}070$	$1{\cdot}337$	$1{\cdot}534$	$1{\cdot}607$
5	Mean stress. $(3p_m) = f_1 + f_2 + f_3$	$-0{\cdot}013$	$+0{\cdot}095$	$+0{\cdot}392$	$+0{\cdot}798$	$+1{\cdot}204$	$+1{\cdot}501$	$+1{\cdot}609$
6	Share in load. f_ξ	$+0{\cdot}369$	$+0{\cdot}432$	$+0{\cdot}613$	$+0{\cdot}884$	$+1{\cdot}180$	$+1{\cdot}413$	$+1{\cdot}502$
	Magnesium.							
7	Principal stresses. $\begin{cases} f_1 \\ f_{3(2)}(=f_y) \\ f_{2(3)} \end{cases}$	$+1{\cdot}108$	$+1{\cdot}083$	$+1{\cdot}027$	$+0{\cdot}983$	$+0{\cdot}983$	$+1{\cdot}011$	$+1{\cdot}026$
8		$-0{\cdot}081$	$-0{\cdot}071$	$-0{\cdot}044$	$-0{\cdot}008$	$+0{\cdot}029$	$+0{\cdot}055$	$+0{\cdot}065$
9		$-0{\cdot}081$	$-0{\cdot}060$	$-0{\cdot}016$	$+0{\cdot}012$	$-0{\cdot}004$	$-0{\cdot}044$	$-0{\cdot}063$
10	Yield potential. $f_{red} = f_1 + f_{2(3)} - f_{min.}$	$1{\cdot}189$	$1{\cdot}154$	$1{\cdot}071$	$0{\cdot}990$	$0{\cdot}987$	$1{\cdot}055$	$1{\cdot}089$
11	Mean stress. $(3p_m) = f_1 + f_{2(3)} + f_{3(2)}$	$+0{\cdot}946$	$+0{\cdot}952$	$+0{\cdot}967$	$+0{\cdot}987$	$+1{\cdot}007$	$+1{\cdot}022$	$+1{\cdot}028$
12	Share in load. f_ξ	$+1{\cdot}108$	$+1{\cdot}081$	$+1{\cdot}020$	$+0{\cdot}992$	$+0{\cdot}983$	$+1{\cdot}019$	$+1{\cdot}026$
	β Tin.							
13	Principal stresses. $\begin{cases} f_1 \\ f_{3(2)}(=f_y) \\ f_{2(3)} \end{cases}$	$+1{\cdot}699$	$+1{\cdot}596$	$+1{\cdot}334$	$+1{\cdot}076$	$+1{\cdot}054$	$+1{\cdot}183$	$+1{\cdot}247$
14		$-0{\cdot}453$	$-0{\cdot}411$	$-0{\cdot}296$	$-0{\cdot}139$	$+0{\cdot}018$	$+0{\cdot}132$	$+0{\cdot}174$
15		$-0{\cdot}453$	$-0{\cdot}376$	$-0{\cdot}185$	$-0{\cdot}024$	$-0{\cdot}100$	$-0{\cdot}299$	$-0{\cdot}389$
16	Yield potential. $f_{red} = f_1 + f_{2(3)} - f_{min.}$	$2{\cdot}152$	$2{\cdot}007$	$1{\cdot}630$	$1{\cdot}215$	$1{\cdot}154$	$1{\cdot}482$	$1{\cdot}636$
17	Mean stress. $(3p_m) = f_1 + f_{2(3)} + f_{3(2)}$	$+0{\cdot}793$	$+0{\cdot}809$	$+0{\cdot}853$	$+0{\cdot}912$	$+0{\cdot}972$	$+1{\cdot}016$	$+1{\cdot}032$
18	Share in load. f_ξ	$+1{\cdot}699$	$+1{\cdot}566$	$+1{\cdot}275$	$+1{\cdot}060$	$+1{\cdot}050$	$+1{\cdot}174$	$+1{\cdot}247$

TABLE XIV.—*Characteristic Stresses in Random Aggregates of Hexagonal (and Tetragonal) Metal Crystals, for Two Singular Orientations and their Surface Intersections, due to Unit Tension Applied to the Random Aggregate.*

Row	Orientation			Metals :	Zinc.	Cadmium.	Magnesium.	Tin.
			Elastic constants.	s_{11} $\;\Big\}$ 10^{-13} sq. cm. per dyne.	+ 8.4	+ 12.3	+ 22.3	+ 18.5
1				s_{11}	+ 8.4	+ 12.3	+ 22.3	+ 18.5
2				s_{12}	+ 1.1	− 1.5	− 7.7	− 9.9
3				s_{13}	− 7.75	− 9.3	− 4.5	− 2.5
4				s_{33}	+ 28.7	+ 35.5	+ 19.8	+ 11.8
5				s_{44}	+ 26.4	+ 54.0	+ 59.5	+ 57.0
6				s_{66}	...	...	...	+ 135.0
7				$1/m$	14.42	8.7	6.4	6.5
8				$E.\ 10^{6}$ lb. per sq. in.	0.245	0.33	0.272	0.365
9	$H0$ $\phi = 0°$	In-terior	Principal stresses.	$f_x = f_y$	+ 0.376	+ 0.369	+ 1.108	− 1.699
10				f_z	+ 0.047	− 0.191	− 0.081	− 0.453
11			Yield potential.	$f_{red} = f_z - f_x$	+ 0.329	+ 0.561	+ 1.189	2.152
12			Mean stress.	$(3p_m) = f_x + f_y + f_z$	+ 0.471	− 0.013	+ 0.946	− 0.793
13	$H0$ $\phi = 0°$ $\psi = 90°$	Surface layer	Principal stresses.	$f_{z,i}$	+ 0.361	+ 0.439	+ 1.134	+ 1.851
14				$f_{z,s}$	+ 0.040	− 0.115	− 0.048	− 0.190
15			Yield potential.	$f_{red,i} = f_{z,s} - f_{min,i}$	+ 0.361	+ 0.554	1.181	2.041
16			Mean stress.	$(3p_{m,i}) = f_{z,i} + f_{x,i} + f_{x,i}$	+ 0.401	+ 0.325	+ 1.086	+ 1.661
17	$H12$ $\phi = 90°$	In-terior	Principal stresses.	f_y	+ 1.447	+ 1.502	+ 1.026	+ 1.247
18				f_z	− 0.268	− 0.104	+ 0.065	+ 0.174
19			Yield potential.	$f_{red} = f_x - f_{min.}$	+ 0.232	+ 0.211	− 0.063	− 0.389
20			Mean stress.	$(3p_m) = f_x + f_y + f_z$	1.715	1.607	1.089	1.636
21	$H12$ $\phi = 90°$ $\psi = 0°$	Surface layer	Principal stresses.	$f_{x,i}$	+ 1.411	+ 1.609	+ 1.028	+ 1.032
22				$f_{y,t}$	+ 1.257	+ 1.320	+ 1.045	+ 1.360
23			Yield potential.	$f_{red,i} = f_{x,i} - f_{min,i}$	− 0.458	− 0.286	+ 0.085	− 0.288
24			Mean stress.	$(3p_{m,i}) = f_{z,i} + f_{y,i} + f_{y,i}$	1.715	1.607	1.045	1.360
25	$H12$ $\phi = 90°$ $\psi = 90°$	Surface layer	Principal stresses.	$f_{x,s}$	+ 0.799	+ 1.034	+ 1.130	+ 1.648
26				$f_{z,ss}$	+ 1.489	+ 1.544	+ 0.999	+ 1.146
27			Yield potential.	$f_{red,ii} = f_{x,yi} - f_{min,ii}$	+ 0.316	+ 0.250	− 0.084	− 0.447
28			Mean stress.	$(3p_{m,ii}) = f_{z,ii} + f_{z,iii}$	1.489	1.544	1.083	1.593
29					+ 1.805	+ 1.794	+ 0.915	+ 0.698

large, and may even cast doubt on the correctness of some of the elastic constants used in the calculations.   Certainly it must be very difficult to obtain fairly correct figures for the elastic properties of a soft material like tin.   Other errors might have affected the so-called observed values of E and $1/m$, such as the probability that the aggregates investigated were imperfectly at random.

A noteworthy source of tessellated stresses is the directionally variable thermal expansion of, for instance, all the metals quoted in Table XIV.   The anisotropy is again circularly symmetrical about the z crystal axis, the coefficient being greatest (a_z) in that direction, and least $(a_{(x-y)})$ at right angles to it.   Besides these figures, Table XV. gives three different sets of linear coefficients of thermal expansion of the random aggregates of the metals concerned, $viz.$, those observed, $a_{obs.}$, those calculated from $a_m = \frac{1}{3}(a_z + 2a_{(x-y)})$, and also those calculated by consideration of the characteristic component system of the tessellated stresses involved, $i.e.$, a_{ch}.   The latter is obtained by putting the values of $s_z = (a_{ch} - a_z)t$ and $s_x = s_y = s_{(x-y)} = (a_{ch} - a_{(x-y)})t$ into the first three of equations (31), then considering the condition of self-compensation for the random orientation, which is :

$$\int_0^\pi (f_z \cos{}^2\phi + f_{(x-y)} \sin^2 \phi)2\pi \sin \phi \, d\phi = 0 \quad . \quad . \quad . \quad . \quad (34)$$

and which results in $f_z + 2f_{(x-y)} = 0$.   This is nothing else but the mathematical derivation of the statistical representation applied in Part II. on the basis of Figs. 8, 9 and 11.   From the above result it follows that :

$$a_{ch} = \frac{2a_{(x-y)}(c_{11} + c_{12} + c_{13}) + a_z(2c_{13} + c_{33})}{2c_{11} + 2c_{12} + 4c_{13} + c_{33}} \left.\begin{array}{c} \\ \\ \\ \\ \end{array}\right\}$$
$$a_{ch} = \frac{2a_{(x-y)}(s_{33} - s_{13}) + a_z(s_{11} + s_{12} - 2s_{13})}{s_{11} + s_{12} - 4s_{13} + 2s_{33}} \qquad (35)$$

The strain energy per unit volume amounts to :

$$U = s_{(x-y)}f_{(x-y)} + \tfrac{1}{2}s_z f_z . \quad . \quad . \quad . \quad . \quad . \quad (36)$$

As has been mentioned above, the principal stresses of the characteristic system are invariably the same in every crystal and of course parallel to the crystal axes.   It is found that the greatest tensile stress, $f_{(x-y)}$, the yield potential, f_{red}, and the strain energy, U, fall or rise respectively in accordance with the coefficients of thermal expansion of the random aggregates.   The stresses were therefore calculated with both the least and the largest figures for the random coefficient.

Two types of surface intersections were considered, $viz.$, with the z crystal axis at right angles to the free surface (suffix " i "; $f_{z,i} = 0$; $f_{x,i} = f_{y,i} = f_{(x-y),i} = f_{red,i}$ not equal to zero), and with the y axis at right angles to the free surface (suffix " ii "; $f_{y,ii} = 0$). These results are compiled in Table XV., together with, for the sake

of comparison, the figures for f_{red} for a thermal change with iron and cementite in any proportion and the maximum possible strain energy involved with $3 \cdot 29 \%$ of carbon as cementite intermixed with α-iron. Whilst the small anisotropy of magnesium can be neglected, the other three metals, $viz.$, zinc, cadmium and β tin show very large values of stresses and strain energy. No further material change may be expected from the superposition of the unknown coupling stress system. The figures for $f_{(x-y)}$ and f_{red} for zinc do not compare unfavourably with those derived in Part I. in a rather questionable way.

The three metals concerned are of a soft and plastic character, which suggests the following considerations. It is certainly impossible for them to stand up elastically to the stresses due to crystal anisotropy when cooled from " high " temperatures, but they will show plastic strain, more or less, in addition to the elastic cooling strains retained. Since all of them are capable of recrystallisation during cooling and even at room temperature, there is, in general, a probability of spontaneous recrystallisation, its degree depending of course on the range of cooling and possibly also on its rate. Since the recrystallisation during cooling will be restricted to some extent, and at room temperature mainly, to those nuclei which had been exposed to the greatest plastic yield, the less strained nuclei will be activated on subsequent reheating, and they will display spontaneous recrystallisation once more. All these recrystallisations, occurring under the influence of the simultaneously applied elastic strains of the thermal stresses due to crystal anisotropy, will be directed automatically towards progressive parallel orientation which involves gradually decreasing strain energy, $i.e.$, less resistance to the process accompanying change in temperature. It should be remarked also that there is only one single factor in nature favouring random crystallisation with materials of any kind, $viz.$, chance, whilst in given cases there are quite a few others operating against it. Consequently it should never be expected that metals with the features of zinc, magnesium and β tin, as indicated in Table XV., would be produced as fairly perfect random aggregates without the application of special methods for that purpose. For fairly parallel orientated aggregates the figures in Table XV. lose even their qualitative validity, since all stresses vanish with perfectly parallel orientation; in the latter case the stresses quoted in Tables XII. to XIV. will also be modified to invariable ones in each crystal to comply with the requirement of $f_\xi = 1$.

For the above reasons all the figures calculated for zinc, cadmium and tin have certainly not more than qualitative validity for metallurgical practice. They strongly suggest, however, that a most attentive study of the properties of more or less parallel orientated aggregates of these metals would have even far greater significance than would such a study of cubic metals. It is to be considered that if single crystals retain individually odd orientations in a bulk

TABLE XV.—*Characteristic Stresses in Random Aggregates of Hexagonal (and Tetragonal) Metal Crystals due to a Change in Temperature of $t°$ C.*

Row.		Metal :	Zinc.		Cadmium.		Magnesium.		Tin.	
1	Linear coefficient of thermal expansion of— Single crystals $\begin{cases} a_2 \\ a_{(x-y)} \\ a_{obs.} \end{cases}$ Random aggregates $\begin{cases} a_m \\ a_{ch} \end{cases}$	in 10^{-6} per °C.	63·9		52·6		26·4		30·5	
2			14·1		21·4		25·6		15·5	
3			30·0		31·6		26·0		23·0	
4			30·7		31·8		25·9		20·5	
5			26·8171		29·1082		25·8615		20·3341	
6	Calculated, for the random expansion, with $a =$		28·8171	30·7	29·1082	31·8	25·8615	26·0	20·3341	23·0
7	Interior. $\begin{Bmatrix} \text{Principal stresses.} \left\{\begin{matrix} f_{(x-y)} \\ f_z \end{matrix}\right. \\ \text{Yield potential, } f_{red} = f_{(x-y)} - f_z \\ \text{Strain energy, } U, \text{ in } [t^2 \times \text{in. lb. per cu. in.}] \end{Bmatrix}$ in $\begin{bmatrix} t \times \\ \text{lb. per} \\ \text{sq. in.} \end{bmatrix}$	+ 73·78	+ 208·36	+ 38·03	+ 121·15	+ 1·61	+ 3·57	+ 51·55	+ 113·69
8			- 147·56	- 55·25	- 76·06	- 21·51	- 3·21	- 1·31	- 103·10	- 44·01
9			221·34	263·61	114·09	142·66	4·82	4·88	154·65	157·70
10			0·003674	0·004376	0·001186	0·001484	0·0000013	0·0000017	0·000773	0·001018
11	Surface layer. $\begin{Bmatrix} f_{red,i} = f_{(x-y),i} \\ \text{Principal stresses.} \left\{\begin{matrix} f_{z,ii} \\ f_{z,ii} \end{matrix}\right. \\ \text{Yield potential, } f_{red,ii} = f_{z,ii} - f_{z,ii} \end{Bmatrix}$ in $\begin{bmatrix} t \times \\ \text{lb. per} \\ \text{sq. in.} \end{bmatrix}$	+ 194·15	+ 253·43	+ 103·52	+ 139·67	+ 2·60	+ 3·97	+ 81·53	+ 126·49
12			+ 62·17	+ 155·56	+ 22·85	+ 72·80	+ 0·95	+ 2·11	+ 21·63	+ 47·71
13			- 170·61	- 120·37	- 89·99	- 65·91	- 3·73	- 2·45	- 129·37	- 82·08
14			223·78	295·93	112·84	138·71	4·68	4·56	142·00	129·79
15	For iron and cementite $f_{red} = 120\cdot86$ $[t \times \text{lb. per sq. in.}]$; and with 3·29% of carbon as cementite $U_{max} = 0\cdot00008520$ $[t^2 \times \text{in. lb. per cu. in.}]$.									

otherwise fairly parallel-orientated, this represents an undesirable singularity. The maximum possible effect of this on the characteristic stresses should be investigated mathematically, and compared with conditions due to perfect random orientation. Such a study should, however, consider also the frequency of very much adversely orientated crystal units, which should be found by experiment. Since perfect random aggregates would need to be produced also for such investigations, the following suggestion is added. Spherically random forging of a specimen should be carried out at an invariable temperature which is equally suitable for severe forging and for quick recrystallisation, ample time being given for recrystallisation between subsequent forging pressures. It would then be interesting to study the behaviour of such random aggregates with different rates of cooling to room temperature and with repeated heating-cooling cycles. It might be expected that they would display a very great tendency to crack formation on cooling.

The above discussion throws serious doubt on the validity of the observed values, $a_{obs.}$, for random calculations, since the samples were most likely of far from perfectly random orientation. The method of calculation for a_{ch} has been criticised before, because the influence of the coupling system of the tessellated stresses was not taken into account; that leading to a_m is theoretically still more doubtful, since it entirely neglects the elastic properties of the single crystal.

It was recently mentioned in a discussion at the Australian Institute of Metals by R. W. K. Honeycombe, M.Sc., of the C.S.I.R. (Australia) Lubricants and Bearings Section, that tin-base bearing alloys showed crack formation after a small number of heating-cooling cycles (15) between 30° and 150° C., and marked cracking after 100 cycles, regardless of whether the bearing alloy was in the form of thin independent slabs or bonded to a steel shell. No similar crack formation was noticed, however, under identical conditions with bearing alloys based on the cubic metal lead, which is, of course, free from thermal anisotropy. It does not matter very much whether the crack formation was exclusively controlled by tessellated stresses due to crystal anisotropy or whether it was also more or less influenced by those of structural type. Actual investigations by Mr. Honeycombe will probably answer this question. It is in any case an uncompromising argument for the vital necessity of the comparative study of the properties of random aggregates on the one hand, and of more or less parallel orientated ones on the other, as has been repeatedly suggested in this series of papers.

Whilst the above confirms how dangerous it is to apply pulsating heating to more or less random aggregates of crystals with thermal anisotropy, it should be considered at the same time that pulsating heating may be of assistance in attempts to orientate a crystalline aggregate. The combination of the range of pulsating heating and the rate of change in temperature should comply first of all with the

requirement for the elimination of crack formation. Some non-metallic materials produced by sintering are exposed to frequent changes of temperature in service. If the crystals are affected by thermal anisotropy parallel orientated aggregates are desirable. This would also increase their load capacity for any body stresses. It may then be asked whether sintering at constant temperature is really the very best that can be done.

A study of the stresses in surface intersections in Table XV. discloses again unpleasant features for zinc, cadmium and tin. Intersections i account for the degree of crystallographic deficiency of random aggregates in selective surface corrosion. While that question has been discussed above, and the surface problem in connection with fatigue especially in Part II., some further remarks will be added regarding the singularity of the surface layer. On studying all the probable degrees of stress relaxation in the present and previous papers of various kinds of tessellated stresses, one may expect, in general, that the reduction of the yield resistance of the surface crystals owing to their being intersected may surpass the effect of stress relaxation. It appears that the surface layer of ductile materials has a singular disposition to initiate both yield and recrystallisation under conditions equivalent to those in the interior of the body. The same may hold for the fracture of brittle materials.

THERMAL CONSTANTS.

Single crystals and perfectly parallel orientated aggregates will display one and the same " local " value of specific heat, *i.e.*, gradient of the curve of latent heat plotted against temperature. Aggregates of more or less random crystalline orientation with thermal anisotropy must deviate from those values on account of the strain energy generated or released on either cooling or heating. Some further complication is involved if plastic tessellated strain develops. Due to it, the aggregate can, in general, not become quite free from tessellated thermal stresses and strain energy at any temperature. The state with least strain energy will correspond to a temperature somewhat different from that at which the aggregate was previously completely free from stresses. A special feature of each of these temperatures is that the local value of the specific heat must be less at temperatures below it, and greater above it, than that of a single crystal or of a perfectly parallel orientated aggregate.

Similar considerations hold also for structural arrangements which involve the development of tessellated stresses on cooling or heating. The local value of the specific heat cannot be exactly equal to the proportional combination of those of the structural components, but must display the same variability as found above, in consequence of the strain energy involved in the structural tessellated stresses.

There is quite a noticeable similarity between magnetic hysteresis

and pulsating heating of random aggregates with thermal anisotropy if the latter procedure is accompanied by regularly alternating tessellated plastic strains. One feature is, however, slightly different. The latter is concerned only with energy forms which are easily transformed into one another, and in a certain sense the thermal balance is not affected at all. The electro-magnetic balance of the former will, however, invariably indicate losses.

The effect of tessellated plastic strains on the coefficient of linear thermal expansion shows another similarity to electro-magnetic hysteresis, since the reversibility of volumetric change is upset to a minute extent. This is apparent with random aggregates of crystals with thermal anisotropy, and also with structural tessellation of components with different coefficients of thermal expansion and with different elastic constants. In the case of such structural tessellation, tessellated plastic strains modify the " local " value of the coefficient of thermal expansion of the aggregate, calculated on the assumption of perfect elasticity, so that it approaches the value obtained by the proportional combination of the expansion coefficients of the structural components. With fluctuating heating which is accompanied by alternating tessellated yield, regular hysteresis curves develop when the thermal expansion is plotted against temperature in both the above-mentioned cases.

If structural tessellation is concerned with components of different thermal expansion but uniform elastic constants, the thermal expansion of the aggregate is exactly equal to that obtained by the proportional combination of the coefficients of the components as long as purely elastic strains are involved. Consequently the question arises whether or not this is " locally " affected by tessellated plastic yield, the process being similar to the two above-mentioned cases; however, this question cannot be settled without further investigation.

MODIFICATION OF TESSELLATED STRESSES.

Since tessellated stresses are by no means beneficial, it is advisable to consider how to reduce and redistribute them. If it is desired to do this over the whole mass of a body, thorough plastic deformation suggests itself as a method for ductile material. The greater the magnitude of the original tessellated stresses, the more severe should the cold-working be in order to achieve a reduction of the stresses to a low value. The redistribution cannot develop uniformly and must be more or less retarded at the junction of single crystals or of the components of structural tessellation. It must be borne in mind, furthermore, that on applying uniform plastic straining to " tessellated " random aggregates, crystals of different orientation and the individual components of structural tessellation undergo greatly varying elastic strains before the start of plastic deformation and that they maintain these elastic strains with not much modification. On gradually finishing the cold-

working and progressively relieving parts of the body from external forces, the above-mentioned "individual" elastic strains which were set up by external forces must become redistributed, so that the residual elastic (strains and) stresses reach equilibrium among themselves. This means that a special "new" system of tessellated stresses is left behind as an after-effect of the cold-working. As cold-working proceeds, these stresses develop with statistical uniformity over the mass and also in its surface layer; hence tessellated tensile and compressive stresses of equal order of magnitude are set up anew.[1] It may be that these "new" tessellated stresses are of a less order of magnitude than were those which had been reduced by cold-working. Tessellated tensile stresses are, however, undesirable even if of moderate magnitude, especially in the surface layer if alternating body stresses or selective corrosion were likely to be set up owing to the (subsequent) service conditions. Cold-rolling is in some ways less harmful than cold-drawing, since the latter is accompanied by great body tension set up selectively in the surface layer owing to heat distortion and shrinkage. This is further aggravated by different types of tessellated stresses in the surface layer, in consequence of its body tension, which combine with those mentioned above.

Thorough cold-rolling appears, therefore, to be an imperfect treatment and cold-drawing a directly dangerous one as regards the retention of locked-up tensile stresses in the surface layer; they cannot, furthermore, be applied at all in numerous cases arising in engineering practice, *viz.*, to components of unsuitable shape or bulky dimensions, or to materials with moderate or poor ductility. All this is not of great concern, however. It is the surface layer which plays a critical rôle, and it appears to be unnecessary in general to pay much attention to the tessellated stresses in the interior of a body. If attention is confined to the surface layer, it is recognised that in nearly all cases some kind of selective cold-working may be found which is actually applicable and leads to unquestionable success. Burnishing, some non-scraping kind of shot-blasting and tumbling are such treatments, and, indeed, they have been applied to all kinds of material ranging from ductile to nearly brittle. It is fortunate that, owing to the reduced yield resistance of the surface layer, a certain degree of cold-working is much more effective when applied to it than when applied to the interior of the body. It is, furthermore, very valuable that small degrees of plastic strain when applied repeatedly and in some alternating manner apparently achieve something like a cumulative effect. Finally, such surface treatments develop compressive body stresses selectively in the surface layer, which are greatly beneficial, since they reduce and possibly transform into compressive ones the tessellated tensile stresses of the surface layer. This means, of

[1] Note that this source of tessellated stresses was not mentioned in either Parts I. or II.

course, a great improvement of the resistance to alternating service stresses and selective corrosion.

Theoretical arguments put forward in the past to explain the beneficial effects of these well-established methods of plastic surface treatment have been based exclusively on the apparent " body " effects of the body compression involved. Experimental investigations definitely suggest that alternating service stresses of considerable magnitude remove gradually the selective body compression of the surface layer and that this is apparently not accompanied by a corresponding reduction in the benefits of the previous treatment. The process of the removal of the body compression of the surface layer by this plastic relaxation must, however, be of a selective character, so that the spots which yield, outwards at right angles to the surface, are those which are subjected to the greatest compressive stresses, these being a combination of the selective body stress of the cold-worked surface layer, its body stress due to service strains, tessellated stresses residual after the cold-working and such as are set up in addition under service conditions. It must be considered in addition that this plastic relaxation may be self-controlled, so that the residual tessellated stresses are not only of the smallest possible order of magnitude but also predominantly of a compressive character, *i.e.*, tessellated tensile stresses are fairly well eliminated, after the relaxation as well. The previous explanations of the mechanism of the beneficial effects of these selective surface treatments would not appear deficient if only static service stresses and/or corrosion were involved. No doubt, their beneficial effect is, however, largely connected, under any circumstances, with the reduction in, or removal of, the tessellated tensile stresses of the surface layer. If such treatments are applied to the surface layer after cold-drawing, both the dangerous types of tensile stresses resulting from the latter—*viz.*, body stresses and tessellated stresses —may be completely removed or transformed into compressive stresses.

DENSITY.

It has been noticed that the density of polycrystalline metals is affected by strain-hardening. Two possible reasons have been previously suggested, *viz.*, the precipitation of, or the progressive transformation to, a " new phase." These explanations would not always be applicable or thoroughly satisfactory. As was pointed out above, strain-hardening must set up a special system of tessellated stresses in general. There are only a few exceptions with polycrystalline material—for instance, in the case of perfectly parallel orientated aggregates of a single kind of crystal or of aggregates of crystals orientated in any way but which, like tungsten, are practically free from elastic anisotropy. The tessellated stresses due to strain-hardening affect the density; they offer a third explanation for the above-mentioned phenomenon.

Density appears, in general, to be a fairly sensitive property of polycrystalline materials. If heating-cooling processes are accompanied by tessellated plastic strains, the magnitude of the latter must depend to a greater or less extent on certain circumstances such as the range of temperature, the rates of heating and/or cooling and possibly the size and shape of the crystals and/or the components of structural tessellation. Since the tessellated plastic strains quantitatively affect the density, the latter must display slight variations even for materials of which the chemical composition and type and proportion of phases and structural components, are the same, and which are examined under equivalent conditions. Similar reasoning holds for the density with regard to tessellated stresses which develop for reasons other than heating or cooling if the process of their development is accompanied by tessellated plastic yield or the formation of hair cracks.

Acknowledgments.

CORRESPONDENCE.

Dr. Ing. W. J. Wrażej (Technical Research Institute, General Staff, Polish Army) wrote : I read Dr. László's three papers about tessellated stresses with much interest, and congratulate him on his many elegant calculations of great importance to metallurgy. I would venture to ask the author a few questions.

Having considered tessellated stresses for β-martensite, is he convinced that such martensite can exist at all ? Certain authors quoted by Epstein,[1] in dealing with that subject, assume that β-martensite contains carbon dissolved in α-iron, as it is in α-martensite, but with the carbon atoms in different places in the α-iron unit cell.

Recently published data [2, 3, 4] have given evidence that, as had been previously found, there is a tetragonality due to the carbon atoms dissolved in the α-iron. This is because the α-iron unit cell cannot under any conditions accommodate a carbon atom without being tetragonally

[1] " The Alloys of Iron and Carbon." Alloys of Iron Research, Volume I.—" Constitution," by S. Epstein. New York, 1936 : McGraw-Hill Book Co., Inc.
[2] N. J. Petch, *Journal of The Iron and Steel Institute*, 1943, No. I., p. 221 P.
[3] H. Lipson and Audrey M. B. Parker, *Journal of The Iron and Steel Institute*, 1944, No. I., p. 123 P.
[4] W. J. Wrażej, *Journal of The Iron and Steel Institute*, 1944, No. I., p. 135 P.

distorted.[1] The tetragonality, as shown by Honda and Nishiyama,[2] changes with the carbon content.

The so-called β-martensite must be regarded rather as consisting of α-iron practically free from carbon with cementite precipitated within it of a size related to the first stage of precipitation, say, a multiple of Fe_3C. An investigation on that subject is in hand and the results will be published later. It would be of interest to know how to deal with the shape of minute particles of cementite, because it would show how to consider other structures such as troostite and sorbite, which give diffused and broadened lines on X-ray pictures, thus proving the presence of internal stresses.

The next question is whether the so-called blue-brittleness can be explained on the basis of the author's considerations. In the description of cubic metal crystals in Part III. I could not find any explanation of the fact that in an aggregate of α-iron grains, when the sample is heated between 100° and 300° C. tessellated stresses could occur owing to differences of crystal (grain) orientation. This range of temperature, as is well known, lies far below the so-called recrystallisation temperature which releases the internal stresses set up when iron is cold-worked.

I assume that if internal stresses, *i.e.*, tessellated stresses, can be produced in the blue-brittle temperature range owing to the inability of particular grains to dilate volumetrically freely, there ought to be a difference between an aggregate and single crystals. In other words, one should expect some difference in volumetric change between a number of rods cut from coarse-grained material (the section of the rods being equal to the section of the particular grain) and a prism of such aggregate of volume equal to the total volume of the rods. In an experiment [3] a number of rods and also a prism of equal volume were sealed in a vessel filled with mercury and closed by a capillary tube ; the mercury expelled on heating was collected and weighed. The difference between the amounts of mercury so collected showed the slight difference in dilatation between the rods and the massive piece. As the temperature rose the difference became noticeable at about 100° C., reached a maximum at a higher temperature and then decreased, becoming nil at 300° C. Above that temperature the mercury outflow was the same in both cases. I assumed at the time that these results could be connected with the freedom of volumetric change when single crystals (rods) are heated. When an aggregate is heated internal stresses (I then called them " (internal) volumetric stresses," but prefer Dr. László's term " tessellated stresses ") ought to be present, and they can influence the brittleness of iron.

I should be much obliged to Dr. László for his opinion on this matter.

I can assure the author that his data and explanation are of great value to metallurgists, who come across many puzzling features in their technical problems.

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[1] The radius of a carbon atom in carbides of simple crystallographic structure according to Öhman (*see* Epstein, *loc. cit.*) is 0·76 Å. The carbon dissolved in austenite when placed at the centre of the cell should have a radius of 0·52 Å. and in α-iron at one of the cube edges 0·36 Å.

[2] K. Honda and Z. Nishiyama, *Science Reports of Tôhoku Imperial University*, 1932, vol. 21, p. 229.

[3] W. J. Wrażej, " Volumetric Internal Stresses as the Cause of the Change of the Properties of Iron at Temperatures between 100° and 300° C.," *Czasopismo Techniczne*, *Lwów*, Apr., 1927.

AUTHOR'S REPLY.

Dr. LÁSZLÓ replied : Since martensite was only considered in connection with structural tessellated stresses in Part I., the term β-martensite was very convenient to denote a great increase in density coupled with practically no alteration in hardness in comparison with α-martensite. If the question arises how to interpret the atomic structure of β-martensite, the answer suggests itself that carbon represented exclusively by cementite proper could not account for the hardness of the so-called β-martensite. It is, however, possible to assume, until experimental evidence to the contrary has been found, that nascent cementite which is forced to fit the atomic spacing of α-iron would cause lattice distortions of sufficient magnitude to explain the hardness. If Dr. Wrażej is concerned with a question of a "structural" nature, the same method may be suggested as F. R. N. Nabarro [1] applied to nascent silver plates precipitating out of the solid solution with copper. If, however, his interest is connected with the diffused and broadened character of the lines of X-ray photographs, Nabarro's method would be of no assistance, but "atomic" considerations would need to be developed.

The above considerations as well as the answer given below to the question regarding blue-brittleness will be best understood after reading a paragraph on "Precipitation-Hardening" of Part IV. of "Tessellated Stresses" to be published later. It is there suggested that the manifestation of increase in hardness beyond values which may be obtained from the proportional combination of those of the structural components, in addition paying due regard to the fineness of the grain, may be more or less a consequence of the considerable strains and strain energy of an indirect and more or less transverse character which would be involved in addition to the "direct" or common shear resistance if slip were to occur. It is furthermore suggested there that brittleness is displayed if the energy required for separation, i.e., the shearing-off of atoms, is less than this strain energy requisite for slip. The analysis of either blue- or temper-brittleness should be attempted by considering the tessellated stresses of the atomic structure. Its strain energy due to some such process of precipitation as is generally assumed to occur with the above phenomena is a supplementary source of the energy required for the separation of the atomic structure. On the other hand, it does not appear probable that either of the above phenomena could be directly connected with the difference in the thermal expansion of single crystals and crystal aggregates. This difference is certainly noteworthy, and would deserve, for itself, special attention.

[1] *Proceedings of the Physical Society*, 1940, vol. 52, p. 90.

VARIABLE HEAT FLOW IN STEEL.*

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and

N. R. EYRES, M.A., D. R. HARTREE, Ph.D., F.R.S., and J. INGHAM, M.Sc. (Physics Department, Manchester University).

(Figs. 4 to 6 = Plates XXIII. and XXIV.)

Paper No. 15/1944 of the Alloy Steels Research Committee (submitted by the Thermal Treatment Sub-Committee).

SUMMARY.

Methods for the calculation of variable heat flow have been devised which take into account the variable diffusivity of the material, latent heat of a change point and almost any surface conditions. Calculations made for the case of a steel ingot cooling in a mould also allowed for the radiative heat transfer across the air gap between ingot and mould and the different thermal properties of the two materials. The range of problems dealt with has been limited by the lack of adequate information on the thermal properties of steel.

Two instruments, one mechanical and the other electrical, have been used for the calculation as well as numerical methods.

The calculations show good agreement when compared with experimental results obtained both in the laboratory and on large-scale masses in industrial furnaces.

A rapid approximate method of obtaining the central temperature of an ingot has been devised. A nomograph and slide rule are given for calculating the soaking time required for uniformity of temperature in industrial practice.

The results suggest improvements in heating technique in industrial furnaces; these are discussed.

PART 1.—PREPARATORY OUTLINE.

§ 1.—*Introduction.*

ALMOST every process in the iron and steel industry is concerned with the heating and cooling of masses of metal, since nearly all such processes, directly or indirectly, require the heating of such masses to a reasonable degree of uniformity, or with quenching them under controlled conditions. The Thermal Treatment Sub-Committee had therefore included in its earliest programme of work the investigation of the whole problem of heat flow, some of which has been reported in the First and Second Reports of the Sub-Committee.[1, 2]

A search of the literature reveals comparatively little that the

industrialist can use in his day-to-day problems. Both experi-
mental work and theoretical papers have, however, been published.*
The former consists of the measurement of the temperature distribu-
tion in a steel mass under a particular set of conditions.   Not only
is it difficult to apply these results to other conditions, but also in
many cases the technique of temperature measurement is such that
the results themselves are open to doubt.   The existing theoretical
work is concerned with the formal mathematical solution of the
equations of heat flow for the special case in which the thermal
properties of the material are independent of temperature, and is
further often restricted to particular variations of the surface
temperature with time.   Thus the application of such a method is
limited to a comparatively few mathematically simple cases, and
frequently involves such simplifying assumptions as to render the
work of little use to the industrialist.

As a first step in their programme, the Thermal Treatment Sub-
Committee had requested the National Physical Laboratory to
determine the physical properties of a number of steels.   When this
information became available [2] it was obvious that the conventional
methods of calculation were incapable of allowing for the large
variations found.   This present work was therefore undertaken to
devise an alternative technique of calculation, which would allow
for variable thermal properties and would be applicable to any
surface heating or cooling conditions.

It is considered that sufficient progress has been made to warrant
the publication of the results so far obtained.   The research has
included practical experiments in the laboratory and works, in
addition to calculations based on the heat-flow equation.   The work
done covers such a wide range of interests that it has seemed advis-
able to deal with the subject in two parts.   The mathematical
method used is the subject of a separate paper,† which will be
referred to here as " the other paper," in which the principles and
their justification are discussed.   The present paper has, therefore,
been restricted to the conclusions from the mathematical treatment
and to the practical aspects, which are dealt with in some detail.

§ 2.—Scope of the Paper.

The object of this research was to develop a general method of
calculating the temperature distribution in a steel mass.   This
method should be applicable to as wide a range of surface conditions
as possible, and should take into account the variation of the
physical properties of the steel with temperature.   The major part
of the present paper is devoted to those problems in which the

* A comprehensive bibliography is provided by the references in Chapter
II. of W. H. McAdams' "Heat Transmission" (New York and London, 1942:
McGraw-Hill Book Co., Inc.).

† N. R. Eyres, D. R. Hartree, J. Ingham, R. Jackson, R. J. Sarjant, and
J. B. Wagstaff, " The Calculation of Variable Heat Flow in Solids," accepted
for publication in *Philosophical Transactions of the Royal Society* (1945).

surface temperature is known, but an illustration is also given in which the rate of heat flow at a surface is controlled by a fourth-power radiation law. As the work developed it was found possible not only to allow for the gradual variations of physical properties with temperature but also to take into account, at least approximately, the abnormal thermal properties in the neighbourhood of a change point. The alteration of the change point in rapid heating or cooling could also be taken into account, if there were sufficient data available.

The work has been pursued in two directions simultaneously, first a mathematical approach from a study of the fundamental laws governing the process, and secondly a purely practical attack in which temperatures were measured inside large steel masses under conditions of industrial heating or cooling. Further, the mathematical work involved a new use of the differential analyser, a calculating machine for the solution of differential equations. This twofold programme resulted in the scope of the work becoming very wide, and it was felt that it should be of interest not only to the steel industry but also to all those who are working on heating processes. For these reasons the description has been divided into two parts, the mathematical work, which is dealt with in the other paper, and the practical work, which is described here. This latter description includes an account of the general principles on which the work has been based as well as of both the machines on which the success of the work depended.

The essential feature of this new technique of calculation is to set up a machine which obeys the same laws as the flow of heat, so that a study of such a machine will, if properly interpreted, give a direct answer to all corresponding problems of temperature distribution in steel masses. The work throughout has been concerned with time-temperature changes on the basis of known thermal properties, and not with any metallurgical changes requiring the operation of a time factor governed solely by metallurgical conditions.

Two machines have been used, the differential analyser at Manchester University, and an electrical computor, which was specially built in collaboration with the Metropolitan-Vickers Electrical Co., Ltd., and operated in the Research Department of Messrs. Hadfields, Ltd., Sheffield. The accuracy of the machines has been checked against algebraic solutions of the heat-flow equations. Solutions obtained by the differential analyser have been compared with results of experiments carried out in the laboratory and the works. Examples of the use of the machine on industrial problems are given in § 7.

During the course of the work a simple rapid method of calculating the centre temperature of a steel mass was developed, which did not involve the use of the machine. Although this method, the time-lag solution (§ 5), is strictly accurate only for a constant rate of heating and a constant diffusivity, it was found to apply to a

large number of problems within the accuracy of experimental measurement.

The experiments, which have been done on a works scale, were originally intended merely to give some idea of the conditions to be found in practice. In particular, two main experiments were carried out, on the solidification of steel in an ingot mould and on the heating of an ingot in a furnace. The results obtained confirmed in a striking manner a number of important conclusions which had been drawn from the theoretical work.

When the differential analyser was later applied to these problems the agreement between calculation and practice was surprisingly good. The work on liquid steel had to be restricted, however, because of lack of knowledge of the physical properties of steel at the high temperatures involved.

Finally, it was felt that the full advantage of this work would not be obtained unless it was possible to place in the hands of the industrial user a means of calculation of soaking times, which, whilst being simple and usable for day-to-day purposes, should yet be accurate within the limits required in the industry. It has been found possible to draw up both a nomograph and a slide rule, either of which will give this information in a very short time. These means should be of value to those concerned in the treatment of large masses, particularly in those cases where ingots are heated singly in a furnace or under equivalent conditions.

PART 2.—THE METHOD OF CALCULATION.

§ 3.—*Theoretical Basis.*

In the early stages of the development of the present method of treating the heat-flow problem, a graphical interpretation of the equations was found helpful in giving a mental picture which suggested possibilities of treatment of the equations by means of a machine. This interpretation of the problem is mainly illustrative, and has been included here so that the results can be more fully appreciated.

The simplest case to consider is that of one-dimensional heat flow in a slab, when the equation governing it is :

$$\frac{\partial \theta}{\partial t} = D(\theta) \frac{\partial^2 \theta}{\partial x^2}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where
θ = temperature at a distance x from the heated surface.
t = time.
$D(\theta)$ = diffusivity of the material of the slab at temperature θ.

In this equation :

$$D = \frac{K}{c\rho},$$

where
K = conductivity of material at point x and temperature θ.
c = specific heat of material at point x and temperature θ.
ρ = density of material at point x and temperature θ.

Although equation (1) is accurate only when there is, at any one time, no variation of the conductivity with the position in the slab, such variations as occur are in general so small as to lead to errors of negligible magnitude.*

The significance of this equation can be seen graphically by reference to Figs. 1 and 2, which show the temperature-distance
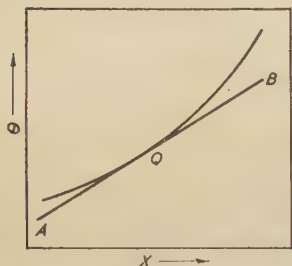
Fig. 1.—Illustration Relating to the Discussion of Equation (1).
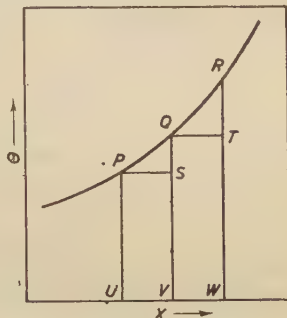
Fig. 2.—Illustration Relating to the Discussion of Equation (1), the slab being considered to be built up of laminæ.

curve through the slab at a time t, and where Q is some point on the curve. The left-hand side of the equation, $\frac{\partial \theta}{\partial t}$, represents the time-rate at which the point Q moves upwards. The right-hand side of the equation, $D\frac{\partial^2 \theta}{\partial x^2}$, can be written in the form $D\frac{\partial}{\partial x}\left(\frac{\partial \theta}{\partial x}\right)$, in which $\frac{\partial \theta}{\partial x}$ is the slope of the curve at any point, for example, the slope of AB at the point Q, and $\frac{\partial}{\partial x}\left(\frac{\partial \theta}{\partial x}\right)$ is the variation of this slope with distance at the point Q.

The slab can be considered as built up of a number of equal laminæ each of thickness δx. The temperature-distance curve in

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* It should be noted that equation (1) is an approximation. The equation of heat conduction in one dimension, when the conductivity varies with the temperature, is :

$$c\rho \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(K \frac{\partial \theta}{\partial x}\right),$$

and use of the form (1) involves neglect of a term $\frac{dK}{d\theta}\left(\frac{\partial \theta}{\partial x}\right)^2$. It can be verified by trial that, except possibly in the initial stages of a quench, this term is substantially smaller than the others occurring in the equation.

the vicinity of the point Q will then appear as in Fig. 2. Here $\dfrac{\partial \theta}{\partial x}$ at the mid-point of the lamina UV is QS/SP approximately, and at the mid-point of the lamina VW it is RT/TQ approximately; the separation of these points is δx, so that the rate of change of $\dfrac{\partial \theta}{\partial x}$ with distance—that is, $\dfrac{\partial^2 \theta}{\partial x^2}$ —is approximately $(RT/TQ - QS/SP)/\delta x$. $SP = TQ = \delta x$, whence approximately :

$$\frac{\partial^2 \theta}{\partial x^2} = \frac{(RT - QS)}{(\delta x)^2} = \frac{(RW - QV) - (QV - PU)}{(\delta x)^2}$$
$$= \frac{PU - 2QV + RW}{(\delta x)^2}.$$

Hence, if θ_P, θ_Q, θ_R are the temperatures at P, Q, R, it follows that :

$$\left(\frac{\partial^2 \theta}{\partial x^2}\right)_Q = \frac{\theta_P - 2\theta_Q + \theta_R}{(\delta x)^2}. \qquad . \qquad . \qquad . \qquad . \qquad (2)$$

Now, the heat-flow equation (1) states that $\dfrac{\partial \theta_Q}{\partial t}$ is D times the value of $\dfrac{\partial^2 \theta}{\partial x^2}$ at Q, the value of D, if variable, being the value $D(\theta_Q)$ appropriate to the temperature at Q. So, use of the approximation (2) in the heat-flow equation (1) gives :

$$\frac{\partial \theta_Q}{\partial t} = D(\theta_Q) \frac{\theta_P - 2\theta_Q + \theta_R}{(\delta x)^2}. \qquad . \qquad . \qquad . \qquad . \qquad (3)$$

Similar equations hold for the temperatures at other points $P, R \ldots \ldots$, and it follows that the rate of rise of temperature at the interface between any two laminæ can be expressed in terms of the three temperatures existing in the interface itself and in its two neighbours. The only exception is, of course, in the case of the surface, as there is material on only one side of it. The argument by which the approximation (2) has been derived here is a rough one, but the result can be justified by more precise reasoning.

For a slab of finite thickness symmetrically heated (and with a symmetrical distribution of temperature through it initially) equation (3) takes a specially simple form if Q is on the central plane of the slab. It is convenient to write θ_0 for the temperature on this central plane, and θ_1 for the temperature on planes at δx on either side of it; by symmetry the temperatures on both these planes are equal. Then, for the time variation of θ_0, (3) becomes :

$$\frac{\partial \theta_0}{\partial t} = \frac{2D(\theta_0)}{(\delta x)^2} (\theta_1 - \theta_0). \qquad . \qquad . \qquad . \qquad . \qquad . \qquad (4)$$

Although the above reasoning has been applied to the case of one-dimensional heat flow in a slab, other cases such as a cylinder

heated radially can be treated in an analogous manner.   In the latter case equation (1) becomes :

$$\frac{\partial \theta}{\partial t} = D\left\{\frac{\partial^2 \theta}{\partial r^2} + \frac{1}{r}\frac{\partial \theta}{\partial r}\right\}, \qquad . \quad . \quad . \quad . \quad . \quad (5)$$

where θ is the temperature at radius r.   If the cylinder is thought of as divided into concentric shells each of thickness δr, and P, Q, R are three points at radii $(m-1)\delta r$, $m\delta r$ and $(m+1)\delta r$, respectively, the approximate equation for this case, corresponding to (3) for the slab, is for points Q not on the axis :

$$\frac{\partial \theta_Q}{\partial t} = \frac{D}{2m(\delta r)^2}[(2m+1)\theta_R - 4m\theta_Q + (2m-1)\theta_P]. \quad . \quad . \quad (6)$$

The corresponding equation for the temperature θ_0 on the axis is :

$$\frac{\partial \theta_0}{\partial t} = \frac{4D}{(\delta r)^2}(\theta_1 - \theta_0), \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where θ_1 is the temperature at radius δr.

Now imagine an instrument consisting of a number of parts, each representing the temperature of a particular interface and so linked together that their motions are related by equations (3) or by (6) and (7).   Then, if the parts representing the temperature of the surface or surfaces are moved so as to follow a given curve of temperature against time, the remainder of the instrument will adjust itself so that it continually represents the temperature distribution in the slab or cylinder, in so far as this is adequately represented by the solution of the approximate equations (3) or (6), respectively.   Two such instruments have been used in the study of the heat-flow problems given in this paper, one mechanical and the other electrical ; their essential principles and the scope of their application are outlined in § 4.

The treatment of heat flow within the material is the same whether the surface condition is a given variation of surface temperature with time, a given rate of surface heat transfer or a given relation between surface heat transfer and surface temperature.   If the time variation of surface temperature is given, it is simply introduced into the appropriate equation of the set (3) or (6), that is, the equation referring to the point Q one layer within the surface ; the main quantitative results of this paper refer to this case.   But, by an extension of the same ideas, it is possible to treat the other kinds of surface conditions mentioned ; an example concerned with radiative heat transfer is involved in the treatment of the cooling of an ingot in a mould, considered in § 8.

Equations (3) and (6) are approximations, and their practical value depends on how close their solutions are to those of the heat-flow equations (1) and (5), respectively.   The purpose of these methods is to enable solutions of these equations to be evaluated for conditions approximating to those of practical interest.   To the inaccuracies introduced by the approximations of equations (3) and

(6) must then be added those due to uncertainty in the thermal data, and there is no value in using more refined methods than the accuracy of the practical data warrants.

The accuracy of the approximation on which equations (3) and (6) are based improves with the number of layers into which the thickness of the slab or the radius of the cylinder is divided; it is approximately proportional to the square of this number. The practical value of this approximation depends on how small a number of layers is required to give results of adequate accuracy; if 1000, or even 100, layers were required, methods based on this approximation would be of no practical value. This aspect has been tested in two ways, first by the evaluation of solutions of both the exact and the approximate equations in some test cases in which both have exact algebraic solutions, and secondly by the evaluation of two solutions for the same surface conditions but with different numbers of layers; from a comparison of two such solutions the errors in each can be estimated. The results show that in the normal processes of heating, annealing and air-cooling, and in the later stages of heat flow in a quench (though perhaps not in the earlier stages), the accuracy obtained by the use of four layers in the half-thickness of a slab (symmetrically heated) or in the radius of a cylinder is better than the reproducibility of the measured values of the thermal properties of different specimens of nominally the same steel, and that often the use of two layers, and sometimes even of one layer, gives adequate accuracy.

This justifies the use of the general method; the practical means of carrying it into effect are considered in § 4.

There is a further approximation in the treatment of varying diffusivity which has been found to be useful in simplifying the application of this method. It extends its range, and often gives results of adequate accuracy for practical purposes. In many cases of practical interest the variation of temperature through the material at any one moment is small compared with the total range of temperature through which the material may pass in the course of time; for example, in the heating of an ingot from room temperature to 1000° C., the variation of temperature through the material at any one moment may well be less than 50°, or one-twentieth of the whole range of temperature covered. It may then be an adequate approximation, except perhaps at temperatures near the change point, to regard the diffusivity as uniform through the material at each moment, with a value appropriate to some mean temperature, although it is not an adequate approximation to neglect the variation of diffusivity over the full temperature range covered by the material in the course of time.

Use of this approximation simplifies the calculation of the solution of the equations for the symmetrical heating of a slab and cylinder and makes it possible to extend the method to two-dimensional heat flow in a cylinder not uniformly heated.

In the latter case the temperature distribution and the heat flow can be divided up into a number of separate contributions in such a way that, if the diffusivity of the material is constant or can be considered uniform at each instant, each contribution can be calculated separately by a simple extension of the treatment used for radial heat flow, and then added to produce the final result, as is shown in detail in the other paper (*see* end of § 1).

§ 4.—*Practical Means of Calculating Temperature Distribution.*

Two instruments have been used for evaluating solutions of the heat-flow equations, one, the differential analyser, being mechanical, and the other electrical. The differential analyser is a calculating machine designed to evaluate mechanically the solutions of differential equations of a wide range of types, and the present is only one of its many diverse applications. The electrical computor was conceived, and designed in experimental form, for this specific problem. Short accounts of these instruments and their capabilities are given here; some further details of them and their application to the heat-flow equations are given in Appendices A and B, respectively.

The differential analyser consists of a number of units interconnected by shafts and gearing. Each unit is a translation into mechanical terms of an operation (integration, addition, &c.) which may be required in the evaluation of solutions of differential equations. Each shaft represents one of the quantities in the equation, and the rotation (total rotation in shaft turns, not angular velocity) is a measure of the respective quantity. Of the work forming the subject of this paper, that part which involved the use of a differential analyser was carried out at the University of Manchester on the machine shown in Fig. 4.

An integrator, of which there are eight in this machine, is a precision form of continuously variable gear. An adding unit is an ordinary differential gear. Input tables serve to provide the machine with information regarding functional relations between variables in the equation, such as the variation of surface temperature with time (if this is one of the data of the problem), or the relation between diffusivity and temperature, in the present application. The result of the operation of the machine can be recorded graphically on an output table or numerically by revolution counters.

In the application of the differential analyser to the heat-flow equations in the approximate forms (3) or (6) it is practicable to deal with surface conditions in the form of a given time variation of surface temperature or surface heat transfer, or in the form of a given relation between surface heat transfer and temperature. It is also possible to include the variation of diffusivity with temperature, and to deal, at least approximately, with the abnormal thermal properties at temperatures in the neighbourhood of the change

point.   The latter has so far been done by regarding the trans-
formation as occurring at a single temperature with absorption or
emission of latent heat.   Actually, in steel the transformation takes
place over a range of temperature, and probably at a rate depending
both on the temperature and on the degree to which the transforma-
tion has already proceeded.   It would be possible to extend the
treatment of heat flow outlined here to cover this situation if
adequate quantitative information were available regarding the
relation between the rate of transformation and the quantities on
which it depends and regarding the thermal properties of the
material through the transformation range, but the necessary
information does not seem to exist.   A suitable treatment would
be expected to provide a quantitative theory of matters such as the
dependence of the change point on the rate of heating or cooling,
the " S-curves " and similar phenomena.
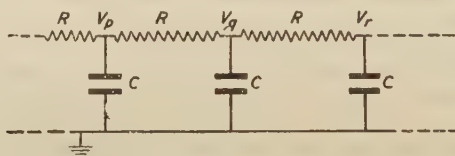
Fig. 3.—Electrical " Ladder Network " consisting of a series of resistance-
capacity loops.

The power of this method of treating the equations of heat flow
will be clear from the above discussion.   Its main limitation is
that the number of intervals into which the thickness of the material
can be divided is restricted by the number of integrators in the
machine.   This is not serious for uniform and symmetrical heating
of a slab or long cylinder.   However, it does become serious when
the extension of the methods to less simple geometrical shapes such
as prisms and short cylinders, or to the non-uniform heating of a
plane or cylinder, is contemplated, and extension to these cases is
desirable, since in practice the heating is not always uniform.
The machine can be applied to heat flow in a uniformly heated
square prism or to two-dimensional heat flow in a cylinder not
uniformly heated, though for these cases the best approximation
within the capacity of the machine is rougher than that which would
normally be used for heat flow in a uniformly heated slab or cylinder.
But its extension to less simple shapes or to the non-uniform heating
of a slab or square prism would require a differential analyser of
capacity greater than any in Great Britain.
The electrical computor was suggested by the similarity in form
between the equations of heat flow in the approximate forms (3) or
(5) and the equation for the voltage distribution in an electrical
" ladder network " consisting of a series of resistance-capacity loops
(see Fig. 3).   In such a circuit the time rate of change of the voltage

V_q across any one of the condensers depends on this voltage itself and on the voltages V_p and V_r across the adjacent condensers on either side. If all the series resistances have the same value R, and all the capacities have the same value C, then :

$$\frac{\partial V_q}{\partial T} = \frac{V_p - 2V_q + V_r}{CR}, \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where T is the measure of time in the transient (*i.e.*, non-steady) behaviour of the electrical network.

Equations (3) and (8) are of the same general form, and can become identical if :

$$\left.\begin{array}{l} \theta = aV \\ t = bT \\ 1/b = CRK/c\rho(\delta x)^2 \end{array}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

where a and (if the diffusivity is independent of temperature) b are constants. It is therefore possible to represent the time variation of the temperature distribution in a slab (in so far as it is adequately represented by the solution of equation (3)) by the voltage distribution in a ladder network of this type. The constant a can be selected arbitrarily to give the most convenient scale for the representation of temperature by voltage. The constant b depends on the properties of the material and the constitution of the electric circuit; its value specifies the relation between the time scales in the thermal and electrical cases.

If a voltage varying with time (on the appropriate time scale) is impressed on the circuit to correspond to the temperature-time curve of the surface of the heated slab, then the temperature at any point in the slab may be obtained by measuring the voltage at the corresponding point in the electrical circuit.

A similar circuit, in which the values of the resistances and of the capacities vary in definite ways along the network, can be devised to handle the equation (5) for symmetrical heat flow in a cylinder (*see* Appendix B), and more elaborate circuits can deal with two- and three-dimensional heat flow, such as that in a bar of circular or rectangular section not uniformly heated.

Such an electrical computor consists of three main parts :

(i) The electrical circuit itself, by which a solution of the equations is obtained in the form of time variations of the voltages at different points of the circuit.

(ii) One or more input units by which time-varying voltages, corresponding to the time variations of temperature of the surfaces of the material, can be applied to the circuit at one or more points.

(iii) An output unit by which the solution is recorded.

An instrument of this kind, of some degree of elaboration, has already been developed by Paschkis and Baker.[3] The instrument used in the present work was conceived independently, and was an

experimental model built by the Metropolitan-Vickers Electrical Co., Ltd. In this instrument, which is shown in Figs. 5 and 6, each input unit consists of a potentiometer in which the position of the movable contact at any moment is adjusted by hand to conform to the ordinate of the appropriate point of the curve of surface temperature against time. The output unit consists of a quadrant electrometer, with one pair of quadrants connected to the point of which the voltage is required and the other to the movable contact of another potentiometer, which is operated continually by hand so as to give a null reading of the electrometer and of which the position is recorded graphically.

The means of applying the time-varying voltages corresponding to the time variation of surface temperature and of recording the results are closely related to the values of C and R to be used in the circuit itself, since manual operation is not sufficiently rapid or accurate if the process of solution takes only a few seconds or less, and longer times of operation call for rather large values of C and R (of the order of microfarads and megohms, respectively) and require that the total electrical leak over a period of several minutes shall be very small. Smaller values of C and R, giving quicker operation, would call for automatic mechanical or electrical means of applying and recording the voltages, but would impose less stringent demands on the insulation. In the instrument here considered, condensers of capacity about 7 microfarads and resistances of 1 megohm were used.

Surface conditions involving given surface heat transfer could in principle be treated by injecting a given current, instead of by controlling the voltage, at a point or points of the network; experimental work on this is in progress.

As already explained at the end of § 3, it is often an adequate approximation to regard the diffusivity as uniform through the material at each moment, but varying in the course of time as the mean temperature of the material varies. With this approximation, the electrical computor can be applied to the calculation of solutions of the heat-flow equations with variable diffusivity. It does not seem impossible in principle to simulate the variation of diffusivity with temperature more accurately by using variable condensers and resistances, but this would introduce considerable complication into practical design and operation, and at present it seems that this aspect of heat flow is much easier to handle by means of the differential analyser. On the other hand, the extension of the use of the electrical computor to two- and three-dimensional heat flow, which even for constant diffusivity is outside the capacity of the differential analyser except in a few simple cases, seems quite practicable, and this (with the restriction to constant diffusivity, or to diffusivity uniform at each moment though varying in the course of time) is probably the most important field for application of an electrical instrument of this kind.

A third, purely numerical, method of evaluating solutions of the approximate equations (3) or (6) has been used in the course of the work which forms the subject of this paper, though the scope of its effective use is more restricted than that of either the differential analyser or the electrical computor. When the use of a single layer from centre to outside of a symmetrically heated slab or solid cylinder gives adequate accuracy, and when the time variation of the surface temperature is smooth and regular, numerical integration of the appropriate equation—namely, (4) for the slab and (7) for the cylinder—provides a quick and easy process for evaluating the central temperature, given the surface temperature, and numerical integration is still practicable if two layers are used. But for more than two layers or for surface conditions other than specified time variation of surface temperature, a purely numerical process becomes rather troublesome.

§ 5.—*Time-Lag Solution.*

In a great number of practical cases a knowledge of the manner in which the temperature of the centre of a steel mass follows that of the surface would be of great value, although a full knowledge of the temperature distribution is not required. It has been found possible to give a simple approximate means of obtaining this information without elaborate calculations.

For a material of constant diffusivity, it was noted by Williamson and Adams [4] that when the surface temperature is uniform and increasing at a constant rate the temperature of each point of the material ultimately increases at the same rate, and that then the difference between the temperature at any internal point P and the surface temperature can be expressed in terms of a time lag.

Williamson and Adams did not give any explicit formulæ for the time lag, but it follows immediately from formulæ (15) and (16) of their paper that under these conditions the time lag between the surface and centre temperatures passing through any particular value is ultimately $\frac{l^2}{2D}$ for a slab of thickness $2l$, and $\frac{a^2}{4D}$ for a cylinder of radius a, independently of the rate of rise of surface temperature.

The general method of calculating approximate solutions of the heat-flow equations used in the present work suggested that these formulæ might be extended to more general conditions. It was, indeed, found possible to use them to estimate, in a uniformly heated * slab or cylinder, the time lag between the surface and centre temperatures, although the diffusivity and the rate of temperature rise were varying. It is only necessary that these variations should be slow, in a sense to be defined shortly, and regular.

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* Uniformly heated as referred to here means heating uniformly round the surface, not necessarily at a constant rate.

Investigation showed that sufficient accuracy for practical purposes could be obtained with heating curves applying in many industrial operations.

In this method the time lag between the surface and centre temperatures passing through the value θ is taken as $\dfrac{l^2}{2D(\theta)}$ or $\dfrac{a^2}{4D(\theta)}$, respectively, where $D(\theta)$ is the diffusivity at the temperature concerned. It is important to realise that, whereas in normal practice the heating curves of the surface and centre are related by considering the difference in temperature at a particular time, the method here suggested is based on the time lag at a particular temperature.

From the point of view of this calculation, " slow " heating means heating in which the rate of change of surface temperature, or mean diffusivity through the mass of steel, varies only slightly in a period of time equal to the time lag. Examination of practical heating curves shows that for normal conditions of heating steel in furnaces, the heating is always slow in this sense, and this is the basic reason why the method gives an adequate approximation under such conditions.

Further, the variation of diffusivity through the mass at any one time is usually quite small except when the temperature is in the region of the change point. During this period the approximation on which the results are based does not apply.

Therefore, when carrying out this calculation the diffusivity is sufficiently accurately defined by taking it as the value at the temperature considered. As an example of the application of the method Table I. has been drawn up, in which the time lag is given for steel No. 5[2] at different temperatures, for six different sizes of cylinder.

In the neighbourhood of the soaking temperature the rate of change of surface temperature usually alters too rapidly for the method to be applicable. A technique for calculating soaking times is given in § 10.

When the method was first evolved it was thought that it might be far too crude for general application, but experience has shown that it often gives the answer correct to practical limits, even under conditions in which it would not be expected to apply. As an example of the type of agreement obtained, a time-lag solution is included in the calculations for the $3\frac{1}{2}$-in. bar given in Table II., § 6.

§ 6.—*Correlation of Calculations with Laboratory Experiments.*

Since both machines had been proved to be capable of solving the formal mathematical equations, it was immaterial which was used to evaluate results for comparison with experimental data. As the electrical computor was still being developed, this comparison was carried out with solutions of the heat-flow equations calculated on the differential analyser or numerically. Since it was essential that the experimental conditions should correspond to a simple

PLATE XXIII.

A.—Integrators.   *B.*—Output table.   *C, D.*—Input tables.   *E.*—Revolution counters.   *F.*—Camera.

Fig. 4.— General View of Differential Analyser at Manchester University.   (*Journal of the Institution of Electrical Engineers*, 1938, vol. 83, p. 643, Fig. 2 ; *Proceedings of the Royal Institution of Great Britain*, 1940, vol. 31, Part I., No. 144, p. 151, Plate I.   Reproduced by courtesy of the two Institutions.)

PLATE XXIV.
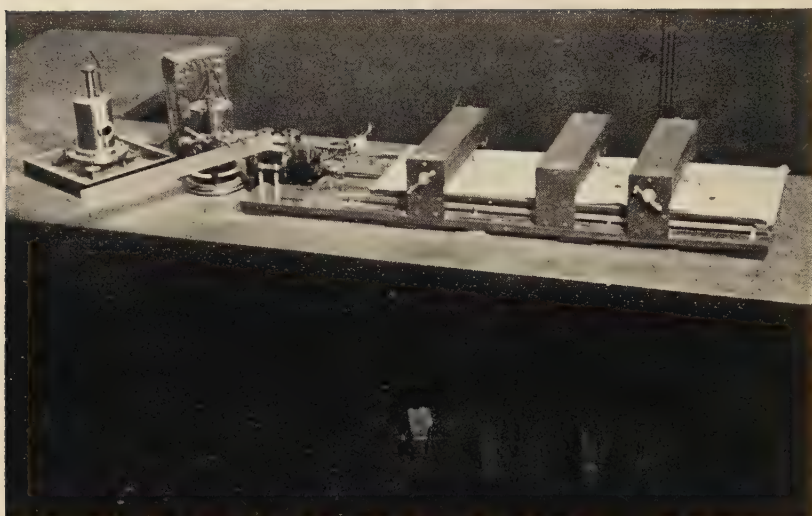
FIG. 5.—General View of Electrical Computor.
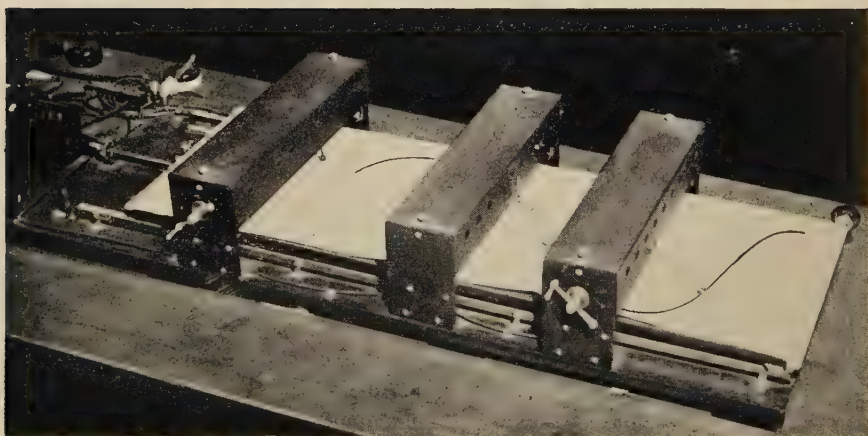
FIG. 6.—Electrical Computor, showing input and output mechanism.

" ideal " case, the determinations were made on a long cylindrical steel bar heated radially, the surface and centre temperatures being measured. Unforeseen difficulties were encountered in this temperature measurement, and for this reason the details of the investigation are given at some length.

The first measurements were carried out on a 12 in. × 1¾-in. dia. bar of acid open-hearth steel of composition carbon 0·41%, silicon

TABLE I.—*Time Lag Between Surface and Central Temperatures of Cylinders of Steel No. 5.*[2]

Diameter. In.:	1.	2.	4.	8.	16.	32.
Temperature. ° C.	Seconds.			Minutes.		
0	3	11	46	3·0	12·2	49
50	3	12	48	3·2	12·7	51
100	3	13	50	3·3	13·3	53
150	3	13	53	3·5	14·0	56
200	4	14	56	3·7	14·8	59
250	4	15	59	4·0	15·8	63
300	4	16	63	4·2	16·8	67
350	4	17	68	4·5	18·1	72
400	5	18	73	4·9	19·5	78
450	5	20	81	5·4	21·6	87
500	6	22	90	6·0	23·9	96
550	6	25	99	6·6	26·5	106
600	7	28	110	7·3	29·3	117
650	8	31	122	8·1	32·5	130
660	9	34	137	9·2	36·7	147
670	10	38	154	10·2	41·0	164
680	11	42	169	11·3	45·2	181
Method not applicable between 680° and 780° C.						
780	10	39	158	10·5	42·0	168
790	9	34	137	9·2	36·7	147
800	7	30	119	7·9	31·6	127
850	7	28	112	7·5	29·8	119
900	7	26	105	7·0	27·9	111
950	6	25	100	6·7	26·6	107
1000	6	24	95	6·4	25·4	102

0·25%, sulphur 0·036%, phosphorus 0·033% and manganese 0·80%. For the centre couple, a hole (¼ in. in dia.) was bored down the axis of the bar to the mid-point, and a base-metal thermocouple was welded to the steel at the bottom. The welding was carried out by a method suggested by Mr. V. M. Hickson,* of the National Physical Laboratory, in which the electric current is carried by a thin copper tube to the junction of the thermocouple, the heat for welding being generated at the point of contact of the couple and the steel. Two

* Private communication.

more couples were spot-welded on to the surface at opposite ends of a diameter through the mid-point of the bar ; each of these couples was thus embedded in a blob of metal on the surface. An open-ended " box " of scrap metal was built up in the furnace, and the temperature was then raised to 1000° C. and the scrap soaked for 1 hr. A high-temperature heat reservoir was thus provided, so that the heating of the bar would be rapid and radial. The thermocouples were connected by means of compensating leads to a mirror galvanometer of 3000 ohms resistance. The bar was then plunged into the box of steel and placed on two small strips of refractory brick.

The temperatures obtained in this experiment are shown in Fig. 7 and compared with the calculated figures ; it is obvious that
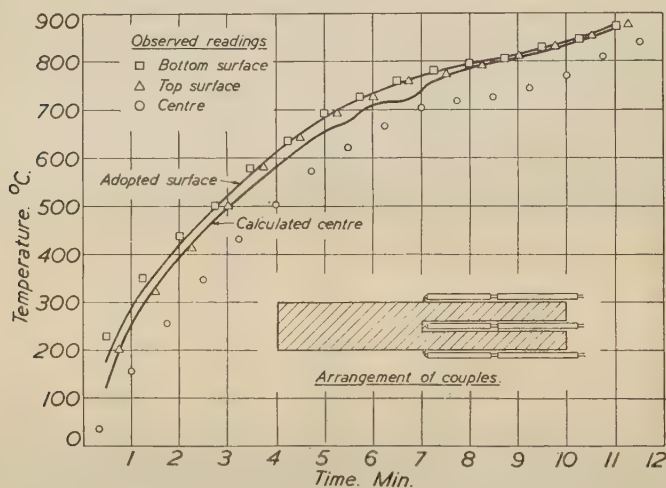
FIG. 7.—Heating of 1¾-in. dia. Bar.   First experiment.

the agreement is bad, although the experimental figures by themselves appear satisfactory. To investigate the discrepancy the experiment was repeated with a modified technique.

In this case the same bar was used as in the first experiment. Two further holes ($\frac{1}{8}$ in. in dia.) were drilled, at an angle of 45° to the surface, to the mid-point of the bar (see Fig. 8). These holes did not meet. One couple wire was welded to the bottom of each hole, the junction being completed through the steel. The surface couple wires were welded into separate grooves $\frac{1}{8}$ in. apart, again at opposite ends of a diameter through the mid-point. The blob of metal left by the weld was ground down flush with the surface. The same procedure as in the first experiment was then followed.

The results of this second experiment were again compared with the calculated values, Fig. 8, and it was found that the discrepancy

was greatly reduced; it seemed probable that the error was due to faulty technique and that the thermocouples were not giving the true temperature of the steel to which they were welded. It was thought that the errors were accentuated by the rapid rate of heating, about 100° C. per min., and it was therefore decided to carry out a further experiment on a larger bar, so that an appreciable difference of temperature between the outside and centre of the steel would be obtained with a slower rate of temperature rise.

The bar used for this third experiment was a 3½-in. dia. bar, 12 in. long, of the same steel as the smaller bar. Temperatures were measured by platinum/platinum–13%-rhodium couples. Four
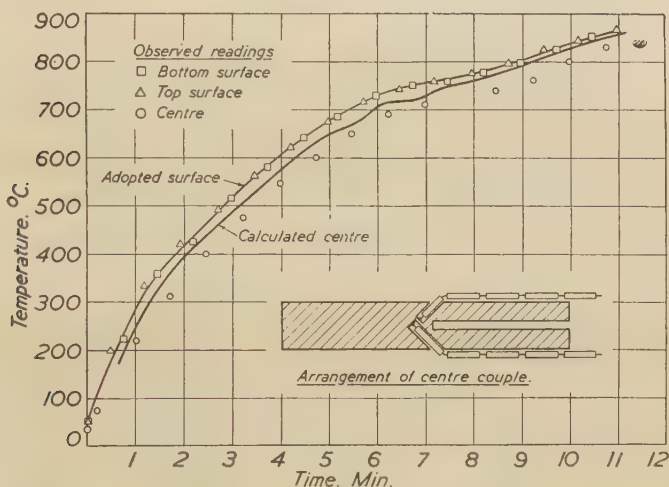
FIG. 8.—Heating of 1¾-in. dia. Bar. Second experiment.

surface couples were welded at points equally spaced round the central cross-section of the bar. The centre couples were welded, one at the bottom of a hole drilled axially and the other at the bottom of two holes drilled at 45° to the surface as in the smaller bar. Thus, both techniques for measuring the centre temperature could be compared. The box of scrap steel previously used for heating was replaced by a circular ingot mould of 6 in. internal diameter and the bar was maintained centrally by welding to it at each end circular flanges which were a loose fit in the mould. The arrangement is shown in Fig. 9.

The experimental and calculated values are given in Table II. and shown graphically in Fig. 10. For the purpose of comparison, the experimental values given in the Table are interpolated from the actual readings obtained.

The agreement between the surface couples was good, particularly after the first 10 min., so that the heating can be considered
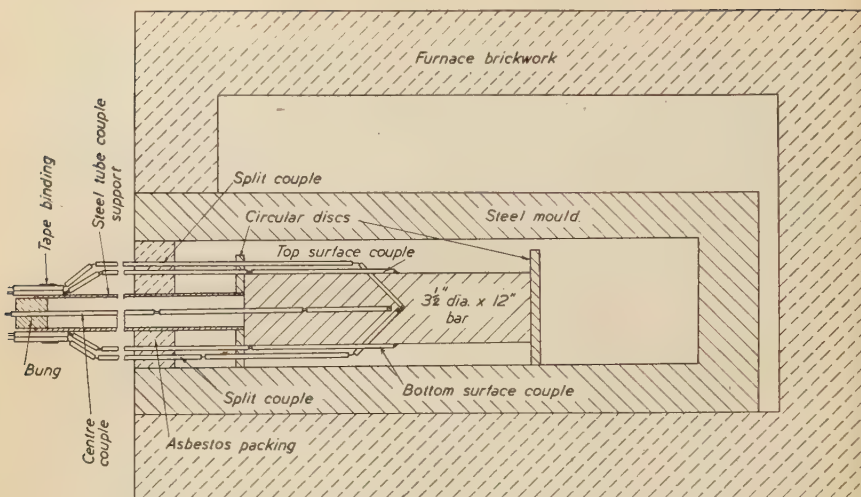
FIG. 9.—Arrangement of $3\frac{1}{2}$-in. dia. Bar during Heating.

TABLE II.—*Results of Heating of a $3\frac{1}{2}$-in. Dia. Bar.*

Time. Min.	Surface Temperature, Observed. ° C.	Centre Temperature. ° C.		
		Observed.	Calculated.	
			By Machine.	Time Lag.
0	25	25	25	25
2	170	114	130	131
4	255	210	226	227
$5\frac{1}{2}$	312	271	283	281
7	368	329	337	335
$8\frac{1}{2}$	421	383	389	386
10	468	433	437	434
$11\frac{1}{2}$	512	477	481	477
13	553	518	521	518
$14\frac{1}{2}$	587	556	558	556
16	619	586	590	588
$17\frac{1}{2}$	647	617	619	619
19	672	644	645	646
$20\frac{1}{2}$	693	664	667	666
22	712	686	685	683
$23\frac{1}{2}$	729	704	701	...
25	740	720	711	...
$26\frac{1}{2}$	742	725	714	...
28	746	726	724	...
$29\frac{1}{2}$	752	728	734	...
31	761	732	743	743
34	785	754	764	765
37	816	794	796	799
40	844	825	829	830
46	882	874	873	874

to be radial. The average of the two values was used for the calculations. There was rather more divergence between the readings of the two centre couples, and, as any experimental errors would be expected to cause a lag in the response and hence a low reading, the higher value, namely, that of the divided couple, is regarded as the more accurate.

The divergence could be caused by one of the couples being off-centre, and radiographs of the bar were taken to verify this point. It was found that the divided couple was $\frac{1}{8}$ in. off-centre, but this would not account for an appreciable temperature difference. The radiographs also revealed that the wires of the axial centre
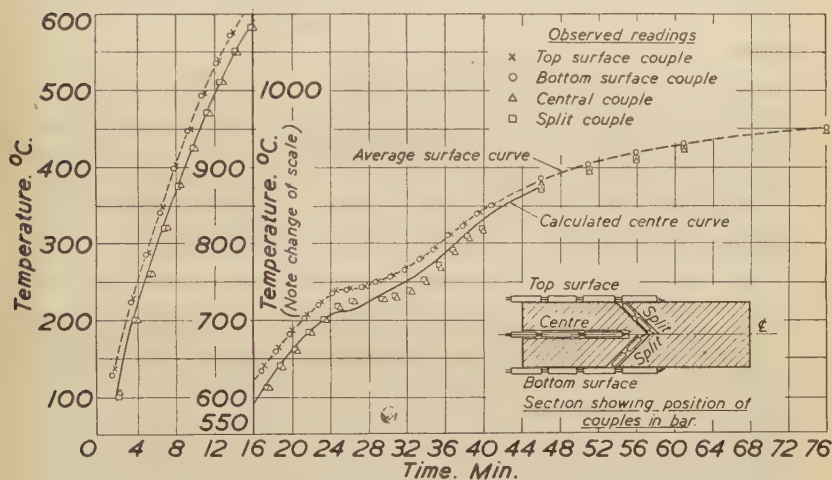
FIG. 10.—Heating of $3\frac{1}{2}$-in. dia. Bar.

couple were in contact for some distance from the point at which the weld was made to the steel. It follows, therefore, that the temperature of the couple junction might lag behind that of the steel which it was designed to measure. The other centre couple showed no such defect.

In Fig. 10 and Table II. results of calculations are compared with the experimental results. The remarkable agreement obtained in this case suggested that a repetition experiment on the $1\frac{3}{4}$-in. bar would prove satisfactory if special attention were paid to the welding of the axial couple. The results of an experiment carried out on similar lines to those with the larger bar are given in Fig. 11. Owing to the small size of the bar the results do not provide a very close comparison between calculation and experiment; also the readings of the two surface couples are somewhat irregular, and the latitude in drawing a " surface-temperature " curve through the readings of the two couples is an appreciable fraction of the time lag between

the surface and central temperatures. It can be seen, however, that the actual errors in the measurement of the temperature were quite small. The experimental results for the $3\frac{1}{2}$-in. bar show greater internal consistency and so form a better basis for the comparison.

This whole series of experiments leads to two important conclusions : First, the agreement between calculation and experiment can be remarkably close ; secondly, measurement of unsteady temperature, even when carried out by an accepted technique, can give erroneous results. That the errors are not easy to detect
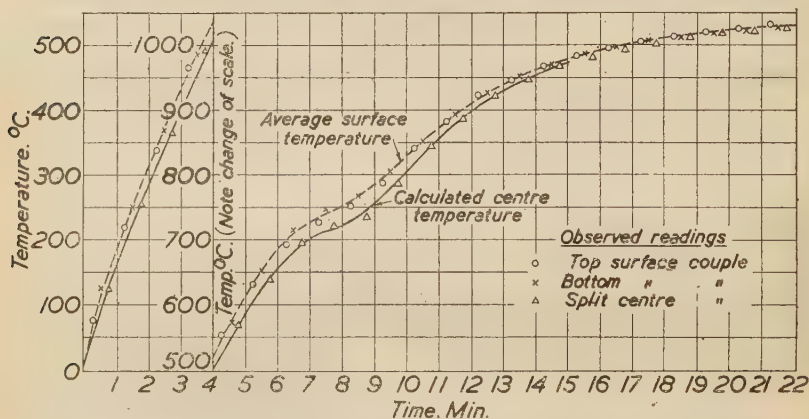
FIG. 11.—Heating of $1\frac{3}{4}$-in. dia. Bar.   Third experiment.

without some form of calculated check is shown by the figures obtained in the first two experiments, which by themselves do not appear to be vastly in error. They were, however, entirely misleading, but the discrepancies did not become obvious until they were compared with a calculation.

PART 3.—LARGE-SCALE PRACTICAL EXPERIMENTS.

§ 7.—*Use of the Machine on Industrial Problems.*

The use of this technique represents the first means of obtaining, without actual measurement, the temperature distribution in steel during heating or cooling under industrial conditions. It is possible to allow for the variation of thermal constants with temperature and, in most cases, for the effects of latent heat ; further, any curve of surface temperature against time can be fed into the machine and the corresponding temperature distribution obtained.

To illustrate the practical value of this work two typical cases have been selected where a detailed study has resulted in a change of practice in the shop with a corresponding saving of time and fuel.

Before considering these cases it must be stated that the calcula-

tions depend on a knowledge of the surface temperature of the steel. In actual practice the steel temperature is measured by a sheathed thermocouple or an optical pyrometer. Where it is practicable to use the latter instrument a true surface temperature is obtained if smoke and flame effects are negligible. In those cases where a thermocouple is used the readings obtained are not a true indication of the surface temperature by an amount which depends on the particular conditions ruling. Up to the present no satisfactory correlation between the two has been found, so that in these cases the thermocouple temperature will be taken as the same as that of the surface. It is thought that the conclusions drawn are not invalidated by this assumption.

Case I.

A bar of steel No. 3,[2] approximately circular in section, of diameter 14·6 in. and length 20 ft. 6 in., which had not completely cooled from forging was placed in a furnace and raised to 875° C., the temperature being taken by means of a rare-metal couple in a heat-resisting steel sheath in the furnace. To exemplify the method and to obtain at least an indication of the order of magnitude of the internal temperature variation in the ingot, the temperatures so recorded were adopted as surface temperatures of the steel for the purpose of calculation.

Since the bar had been cooling down, the centre was at a higher temperature than the surface when placed in the furnace. The effect of this has been estimated by comparing the case in which the centre and surface are considered to be at the same temperature at the beginning of the heating with that in which the centre is taken as 100° C. higher than the surface at the time. Preliminary work showed that this figure was likely to be in excess of the true one.

The calculated time-temperature curves obtained by the differential analyser are shown in Fig. 12. It is seen that the effects of a difference in temperature between the centre and surface of 100° C. at the beginning of heating are eliminated after 45 min. in the furnace. This leads to the conclusion that when a hot charge is placed in a furnace a long period of soaking before the temperature is raised is probably unnecessary. In many cases time can be saved by heating up the charge straight away and omitting this preliminary period which may serve no useful purpose.

The surface temperature reached 875° C. in 8¾ hr., and the centre approached within 5° of this temperature ½ hr. later. The surface temperature during soaking varied by 10° from its mean value, so that a 5° difference through the bar may be taken as a sufficiently close approximation to uniformity for practical purposes. It should be borne in mind that these calculations are based on the heat flow in the steel and take no account of the time required to even-up the furnace itself. Only in the more modern plants is the furnace chamber uniform immediately it has reached temperature;
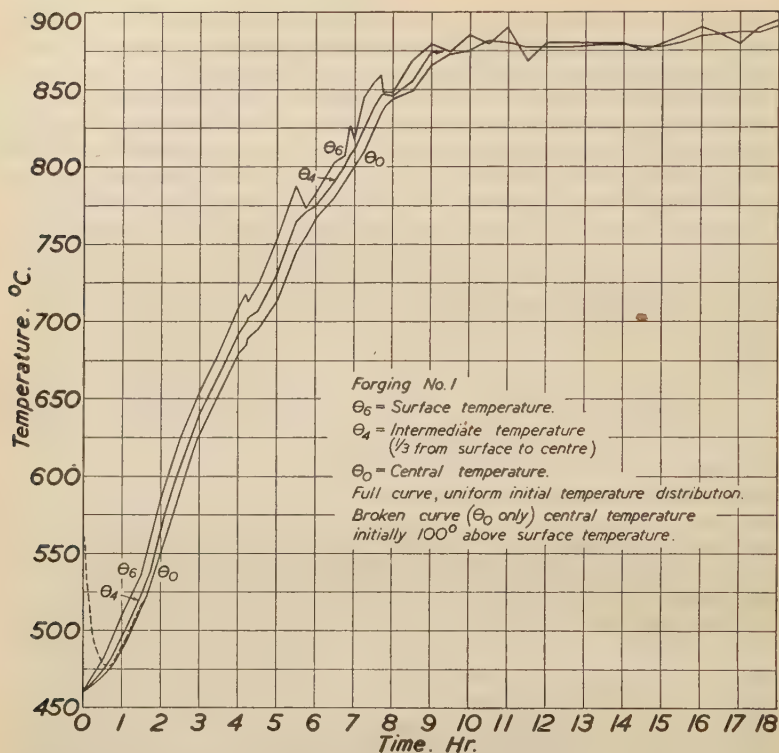
FIG. 12.—Heating of 14·6-in. dia. Forging, showing surface, centre and intermediate temperatures.
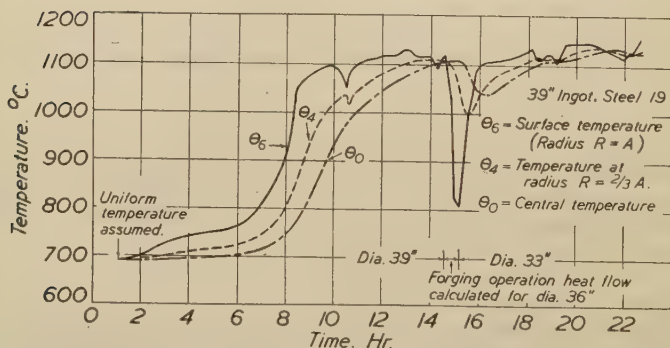
FIG. 13.—Heating, Forging and Reheating of 39-in. Ingot.

in most cases the hearth is considerably colder than the crown, and in these instances additional time is necessary to attain uniform conditions in the furnace. Further, it may happen that the metallurgical reactions take a finite time to complete. Data on this last point appear to be meagre in the extreme, but it seems that only in special cases is this point of importance.

Case II.

An octagonal ingot, 39 in. between the flats, of steel No. 19 [2] was heated for forging. The temperature was observed by means of an optical pyrometer sighted on the top of the ingot. The time-temperature curves for the ingot are given in Fig. 13, and cover the heating, first forging and reheating periods. The curves given are for the observed surface temperature and the calculated temperatures at the centre and at a point two-thirds of the radius from it.

At the start of the heating period the ingot was soaked for 5 hr. and then heated rapidly, reaching the final forging temperature of $1120°$ C. in 6 hr., when it was soaked for a further $2\frac{1}{2}$ hr. The ingot was then withdrawn from the furnace, forged to 33-in. dia. bar and replaced in the furnace for further heating.

For the purposes of the calculation the diameter of the mass during the forging process has been taken as 36 in., the mean of the initial and final dimensions. The ingot has also been assumed to be of uniform temperature when placed in the furnace. Any variations from this will, as shown by case I., have only a small effect. The heat evolution by internal work done during forging has been omitted, since little is known quantitatively in this case about its distribution. If this were known it could be included in the solution of the heat-flow equation by the differential analyser.

The calculations of the centre temperature show clearly that the temperature gradient in the steel is considerably greater during the heating operation than during the preliminary soaking period. Under these conditions the soaking period of 5 hr. at the start would seem of little advantage.

It is also interesting to note that the drop in temperature of the surface about 10 hr. from the start had no effect whatever at the centre. Finally, the behaviour of the centre temperature during and after forging can be clearly seen. It is to be noted that in this case the centre is coldest $\frac{1}{2}$ hr. after the steel is put back in the furnace, and in fact it is cooling most rapidly when the surface is heating most rapidly. Further, although the surface temperature fell to $810°$ C., the centre temperature did not drop below $1040°$ C. This leads to the conclusion that the second heating can be comparatively short.

Some General Comments.

A general conclusion from all the calculations of heat flow that have been carried out in the course of this work is that, provided

that the temperature throughout the steel is nowhere in the neighbourhood of a change point and that the thermal properties depend on the temperature only and not on the thermal history of the material, the internal temperature distribution at any time depends to a considerable degree only on the surface temperature during an immediately previous period, of the order of twice the time lag as given by the formulæ in § 5 ; earlier stages in the variation of the temperature distribution through the material have little effect on the internal temperature distribution at this time or subsequently.

An example is provided by case I. of this section, in which the central temperature after about 45 min. was found to be practically independent of the initial temperature distribution assumed ; the time lag in this case is about 30 min. Another example lies in the success of the time-lag method for estimating the central temperature in a symmetrically heated plate or cylinder. This success would not be achieved if the initial conditions had an appreciable effect on the subsequent temperature distribution after a period of about twice the time lag.

Another example is provided by the results shown graphically in Fig. 13 ; here the effect of the surface cooling during forging disappears in about 3 hr., which is twice the time lag.

A consequence is that results of calculations of the temperature distribution above the change point in a heated mass of steel are not vitiated by the rather rough approximation used for representing the thermal properties through the transformation region.

This same fact also forms the basis for the method of calculating soaking times considered in § 10.

§ 8.—*Cooling of Ingots in Moulds.*

The results considered above show, first, that the equations of heat flow, in the form in which they have been taken, provide an adequate representation of the heat flow in masses of steel (except perhaps at temperatures in the neighbourhood of the change point), and, secondly, that with the help of the differential analyser it is practicable to evaluate solutions of these equations, at least for simple geometrical shapes such as a slab uniformly heated over each face and a long cylinder uniformly heated over its curved surface.

The success of this work suggested an exploration of the possibility of applying the same technique to the calculation of the heat flow in the more complex case of an ingot cooling in a mould, for which some experimental results had recently been obtained. Three additional factors are introduced in this study. These are the formation of an air gap between the ingot and mould, the difference in properties of the steel ingot and the cast-iron mould, and the effects of the liquid state of the ingot existing initially.

The problem has been studied experimentally and by calculation.
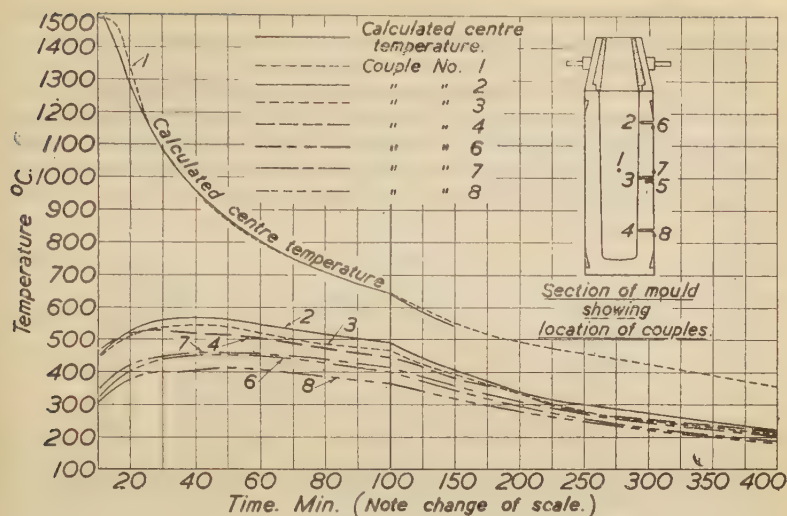
FIG. 14.—Cooling of 9-in. Ingot in Mould.

The Experiments.

The tests were carried out on three sizes of ingots. Medium sizes were chosen, as small ingots would cool too rapidly and big ones would be too unwieldy and expensive. The sizes chosen were 9 in., 11 in., 12 in. square. The steel used was of a composition
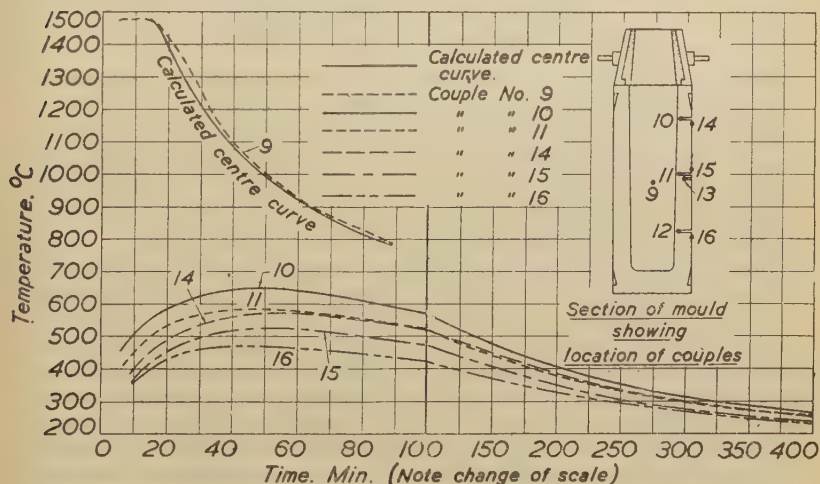
FIG. 15.—Cooling of 11-in. Ingot in Mould.

approximating to steel No. 12, of the Thermal Treatment Sub-Committee.[2]   The moulds used were of cast iron with a refractory head.

The moulds for the three ingots were prepared by drilling, and base-metal thermocouples were welded at the bottom of holes and on the surface of the moulds, as shown in Figs. 14, 15 and 16.   The moulds were arranged in a row on the floor of the shop, their faces in which the couples were embedded being on the same side of the row.
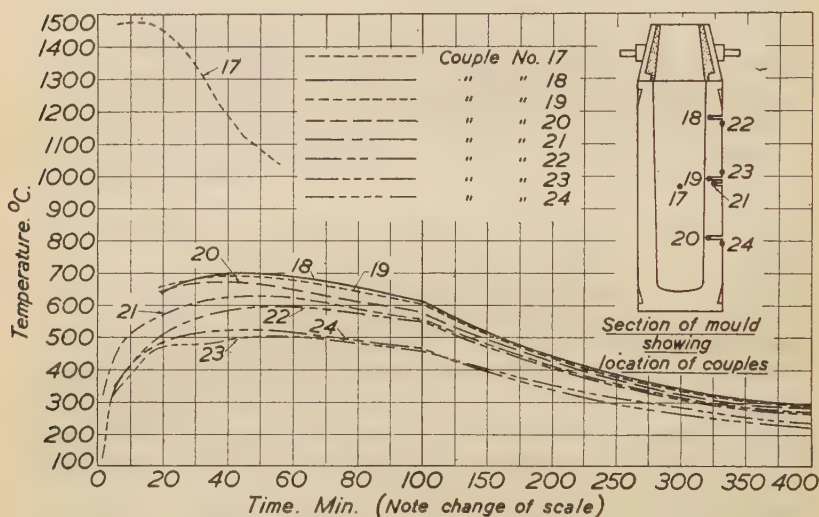
FIG. 16.—Cooling of 12-in. Ingot in Mould.

The temperatures in the centres of the ingots were measured with rare-metal thermocouples and a Tinsley potentiometer.   The couple itself was protected with a $\frac{1}{2}$-in. internal diameter silica sheath, which was itself protected by a length of $\frac{3}{4}$-in. internal diameter by $\frac{1}{4}$-in. wall hydraulic tubing, one end of which was closed.   This tube was maintained centrally in the ingot by means of a steel " spider " fitting over the top of the ingot mould.

The results of the temperature measurements are shown graphically in Figs. 14, 15 and 16.   It will be seen that the freezing point of the steel is clearly defined.   From the length of time, 7–8 min., during which the temperature remained constant it is reasonable to suppose that this was a true indication of the freezing point, and not merely an effect due to the metal protection tube. During a repeat experiment some of the couple readings were not confirmed, and these have therefore not been included in the results.

It is interesting to note that the time taken for solidification was in every case less than the time for the mould to reach its maximum

temperature, *see* Table III. This suggests that up to the end of the solidification period, little of the heat released from the ingot had been transferred through the mould to the atmosphere, the greater part still being held by the mould.

This conclusion is of importance when it is realised that these ingots were not in a casting pit but on the floor of the shop, where the loss from the mould surface would be greater than normal.

TABLE III.—*Times for Solidification and Maximum Mould Temperature.*

Ingot Size. In.	Time to Solidify. Min.	Time for Mould to Reach Max. Temp. Min.
9	14	40 approx.
11	16	40 ,,
12	17	40 ,,

Nevertheless, as the heat of solidification is mainly taken up by the ingot mould, the time of solidification would be largely unaffected by such an alteration.

Calculations.

Heat flow in the ingot cooling in a mould takes place by conduction through the material of the ingot and the mould walls and by radiation across the gap between them. The radiative heat transfer across the gap depends on the temperatures of the outer surface of the ingot and of the inner surface of the mould, but is independent of the width of this gap (which is fortunate in view of the slender knowledge of this width); its dependence on the temperatures of the surfaces bounding the gap can be derived from Stefan's law and the emissivities of these surfaces.

For the evaluation of the relevant equations by the differential analyser the treatment of the heat flow through the material of the ingot and mould follows the method of which the application to simpler systems has been indicated above; different thermal properties for the steel ingot and cast-iron mould introduce no difficulties. New features are, however, introduced by the relations between the temperature gradients at the surface of the ingot and inner surface of the mould and the radiative heat transfer between the surfaces, and it proved practicable to include these relations in the differential analyser set-up.

Calculation of a solution of the heat-flow equations requires knowledge of the initial temperature distribution and the time variation of the surface temperature. Attempts were made to start the calculation from the pouring of the ingot, but lack of reliable quantitative information about the thermal properties of steel through the solidification range made this work unsatisfactory, and

to avoid this difficulty calculations were started from the time at which the observed central temperature of the ingot started to fall. The temperature distribution through the mould wall at this time was taken from the experimental results, and it was possible to derive from this and the central temperature of the ingot an estimate of the temperature distribution through the ingot.* This estimate was probably fairly good, and in any case the temperature distribution after the first few minutes would probably not depend very much
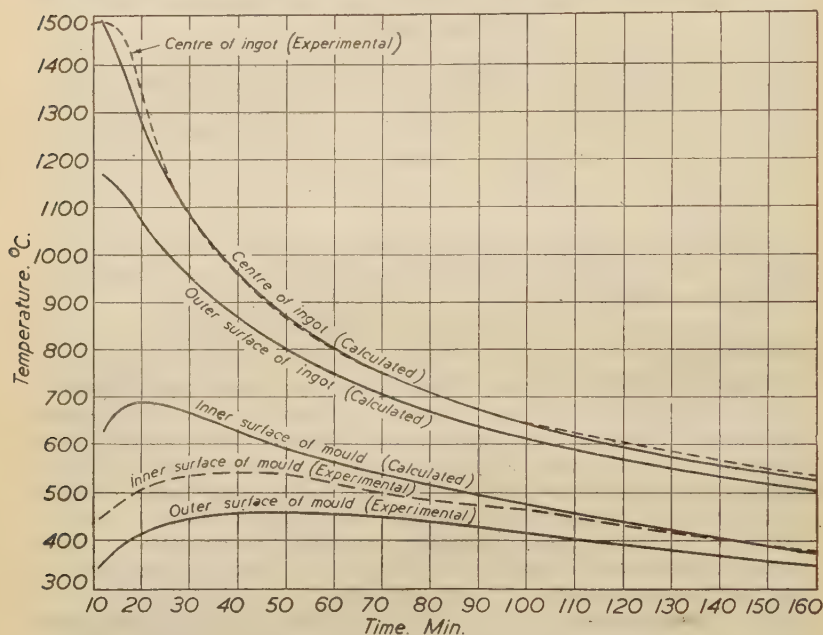
FIG. 17.—Cooling of 9-in. Ingot in Mould, showing results of calculation.

on the initial temperature distribution taken. Once the calculation was started, the only experimental information used was the outer surface temperature of the mould.

The work so far done in this field was intended to be purely

* At the time when the calculations were made it was thought that the measured temperatures at the inside of the mould wall were unreliable, but that those at the centres of the mould walls (couples 5 and 13) were reliable; the estimate of the initial temperature distribution was therefore based on the readings of couples 1, 5 and 7 in the 9-in. ingot, and similarly for the 11-in. ingot. A later repeat experiment suggested that couples 5 and 13 were unreliable but 3 and 11 reliable. There has been no occasion to doubt the temperature of the mould surface on which the calculations mainly depend.

exploratory in character, and in view of the lack of accurate know-
ledge of the thermal properties either of steel in the high-temperature
range (1000° C. to the melting point) or of cast iron over the range
covered by the temperatures attained by the mould (up to about
600° C.), it seemed an adequate approximation for such exploratory
work to take the diffusivity as constant for each material.

The thermal properties were taken for both ingot and mould as
those for steel No. 12 at high temperatures, namely, $D = 0.064$ c.g.s.
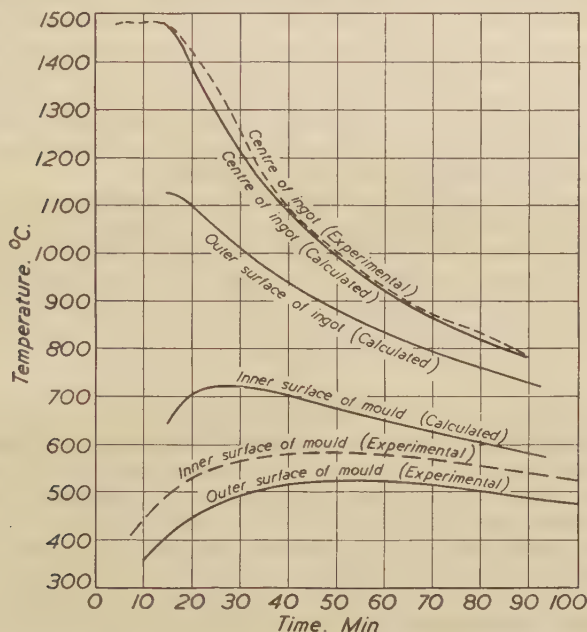
FIG. 18.—Cooling of 11-in. Ingot in Mould, showing results of calculation.

units and $K = 0.08$ c.g.s. units. The values for cast iron were not
certain, but those available suggested that the above figures were a
reasonable approximation at the temperatures concerned. The use
of the same values for the thermal properties of the ingot and mould
was incidental and not due to restrictions imposed by the method of
calculation. The emissivity of the surfaces of the air gap was taken
as 0.9, and the thickness of the mould as $3\frac{1}{2}$ in.

Some results calculated on this basis are given in Fig. 17 (for the
9-in. ingot) and Fig. 18 (for the 11-in. ingot). They show the time
variation of temperature, calculated for the inner surface of the
mould and for the outer surface and the centre of the ingot. The
observed temperatures at the centre of the ingot and both surfaces
of the mould have also been included.

It will be noted that for both ingots the temperature of the mould remains below the change point of the steel, whereas the temperature of the ingot remains mostly above that point, so that the use of a constant diffusivity for both is probably a fair approximation.

The agreement between the calculated and observed central temperatures is quite remarkably close in both cases but unsatisfactory for the temperature of the mould inner surface.   This latter disagreement may be due to difficulties of experimental technique or to lack of information regarding the thermal constants essential to the calculation.   It must be remembered that, apart from the initial temperature distribution, the only experimental information used in the calculation is the time variation of the temperature at the outer surface of the mould.   The crossing-over of the curves of calculated and observed central temperatures towards the end of the time studied is probably a result of the latent heat of transformation, which has not been included in this calculation.

The results show that calculation of heat flow in ingots cooling in a mould is practicable and gives results in at least general agreement with observation.   It would be practicable to include the variation of diffusivity with temperature and the latent heat of transformation, and probably also the latent heat of solidification in the early stages, if adequate quantitative data about these thermal properties were available to justify their inclusion.

§ 9.—*Heating of an Ingot.*

As the research progressed it became increasingly obvious that the soaking times deduced from calculated solutions of the heat-flow equations were always shorter than those given in industrial practice. Before questioning the rules which had been established by many years of experience it was obviously necessary to measure the temperatures actually occurring in a large steel mass heated in an industrial furnace.   An attempt was therefore made to measure the temperature distribution in a 12-in. square ingot of steel No. 5 [2] heated in a typical works furnace.   The furnace was abnormally large for this charge, but this should not invalidate the conclusions of the experiment, although it might tend to greater uniformity than would normally be obtained.

The town-gas-fired bogie furnace, 7 ft. 3 in. × 11 ft. × 4 ft. high, had been down for at least four days and was therefore cold. The ingot was placed longitudinally in the furnace, resting 3 in. above the hearth on firebricks.   The measurement of temperature was carried out by welding chromel-alumel thermocouples at the bottom of holes drilled in the ingot.   No attempt was made to protect the couples from the furnace gases, because earlier experiments had shown that satisfactory protection was impracticable. Further, it was found that bare base-metal thermocouples would retain their calibration for a reasonable time in a town-gas-fired furnace.   The temperatures were obtained from a potentiometric

recorder and a calibrated galvanometer. The details of the positions of the thermocouples are shown in Figs. 19 and 20 together with the temperatures obtained. It can also be seen that an additional couple (the furnace couple) placed in a heat-resisting steel sheath resting on the top of the ingot was used. This was done so that a comparison would be obtained between the actual surface temperature of the steel as measured by a couple welded to it and the readings of the routine furnace couple.
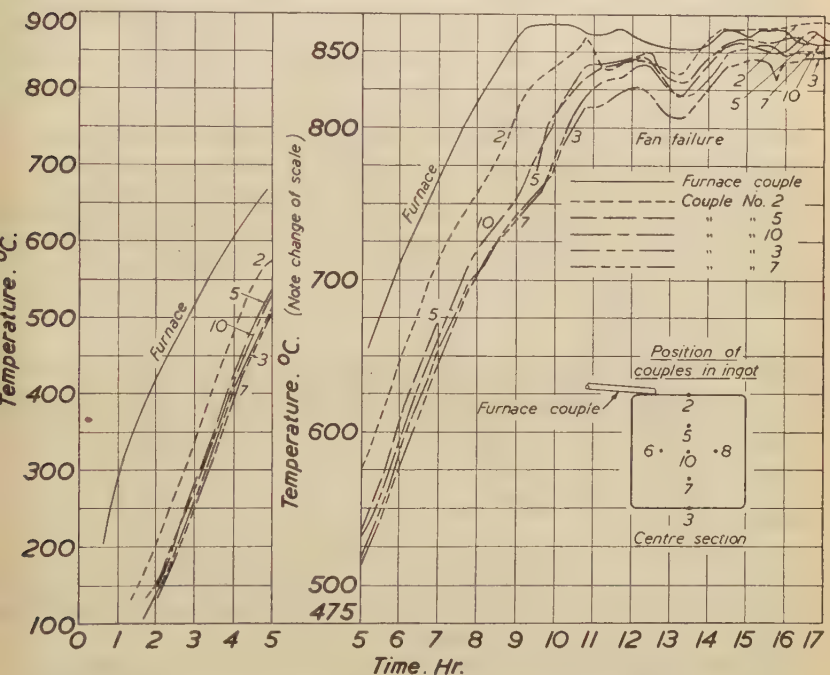
FIG. 19.—Temperatures in 12-in. Square Ingot during Heating.

From Fig. 19 it can be seen that during the 9 hr. heating up, the furnace couple was always at a higher temperature than the top of the ingot with which it was in contact, the temperature difference decreasing from 200° to 50° C. The temperature of the top surface of the ingot continued to rise for a further 2 hr. after the furnace couple had reached temperature. The kink in the curves 13 hr. after the start was due to failure of the air fan.

It should be noted that the temperature of the bottom of the ingot approached to within 20° C. of that of the top surface 12 hr. after the start of the test, and the uniformity was not improved by a further 5 hr. soaking. At the time when observations were stopped there

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was an appreciable temperature drop through the ingot.   The same was, in general, true throughout the whole period, and it was quite obvious that little or no heat entered from the underside of the ingot.   This means that heat was always flowing through the ingot into the hearth of the furnace, despite the fact that the ingot was supported on bricks and any heat transfer was by radiation to the hearth.   The flow of heat through the ingot is confirmed by the
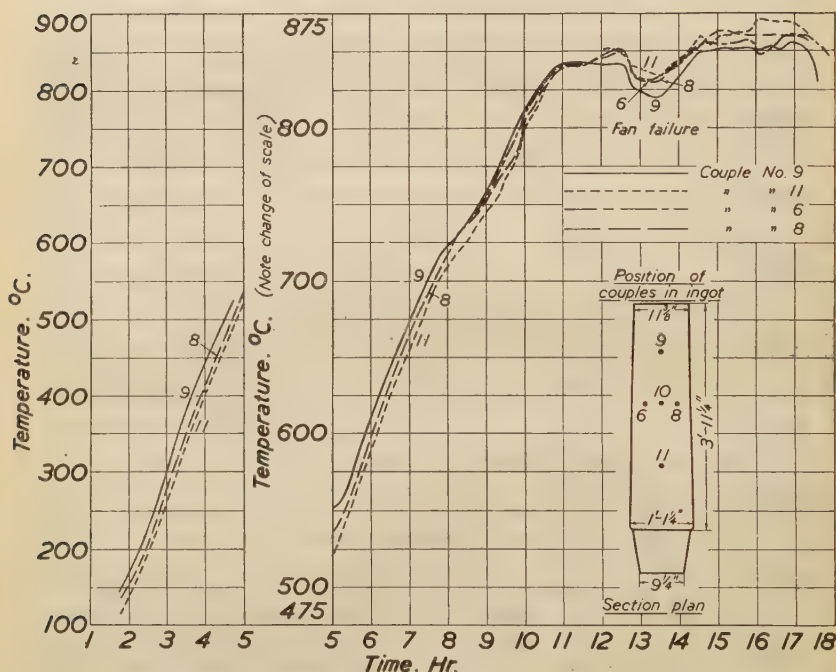
FIG. 20.—Further Temperatures in 12-in. Square Ingot during Heating.

intermediate couples, which show a temperature drop from top to bottom throughout the soaking period.

Although the ingot was soaked for 8 hr. after the furnace couple reached temperature, there was no improvement in uniformity after the first 3 hr.   It is obvious that the temperature gradient in the steel was being maintained by the cooling effect of the hearth, and that had this cooling not been present the soaking time would have been shorter and about 3 hr. would have sufficed to allow reasonable uniformity.

This experiment confirmed a number of most important conclusions which had been suggested by the general trend of the whole research.   Although the steel virtually attained a steady temperature

in a short time, uniformity within the mass would remain unsatisfactory until the furnace brickwork itself had reached a uniform state. In this particular experiment a comparatively small mass of steel was heated in a large furnace, and it is therefore reasonable to suppose that in common practice, where the hearth is more completely covered, the conditions would be considerably worse.

This leads in turn to the conclusion, of great practical importance, that in industrial furnaces in which a high throughput is required steps must be taken to heat the hearth of the furnace as well as the crown. In a large proportion of the furnaces at present in use the so-called soaking time of the charge is in reality the soaking time of the furnace itself.

Previous to this work, it was held in many quarters that a furnace was heated satisfactorily if the heat was pumped in near the crown and flame impingement was avoided. Particularly was this thought to be true for high-temperature work, where radiation tends to even-up the furnace temperature. Now it can confidently be stated that when a furnace is designed much greater attention must be paid to the method of heat input. In the ideal furnace the heat would be put in so that all parts of the furnace brickwork tended to supply heat to the charge at the same rate.

In view of the results of this experiment it is deemed possible that even the most difficult steels to heat-treat might be heated more rapidly than is commonly supposed if only the furnace temperature is raised uniformly during the heating. In short, it may well be that the lack of uniformity of temperature in the furnace is the real cause of clinking and that the temperature gradients in the steel mass itself would not be dangerous if only the steel were heated equally from all directions.

Some time after this experiment was made it was realised that the methods of the present paper for calculating solutions of the heat-flow equations could be extended to non-symmetrical heat flow in a cylinder (*see* end of § 3). The method, as so extended, has been applied to one set of the observations made in this experiment, namely, those for the central section of the ingot. Unfortunately, only two of the four surface couples gave any readings, so that data regarding the variation of surface temperature round the ingot are not as complete as could be wished. Further, graphs of the measured temperature distribution along the vertical diameter (couples 2, 5, 10, 7, 3) at various times strongly suggested a systematic error in the temperatures recorded by at least one of the couples, probably No. 5. For the purpose of calculation it was decided to adopt the values of the surface temperatures (couples 2 and 3), but to smooth them slightly so as to simplify calculation (which was done numerically) and to assume symmetry about a vertical plane through the axis of the ingot. Results calculated on this basis for the temperatures at the positions of the three internal thermocouples are shown

in Fig 21, both as functions of the time and as functions of the position along the diameter at different times.

The calculated variation of temperature along the diameter is very nearly parabolic, with the coldest point at or near the bottom of the ingot. Comparison with the measured temperatures is satisfactory for couples 10 and 7, and suggests that the readings for couple 5 were systematically low; the fact that this couple failed completely for a time in the course of the experiment also suggests that it is the one of which the readings are most dubious.
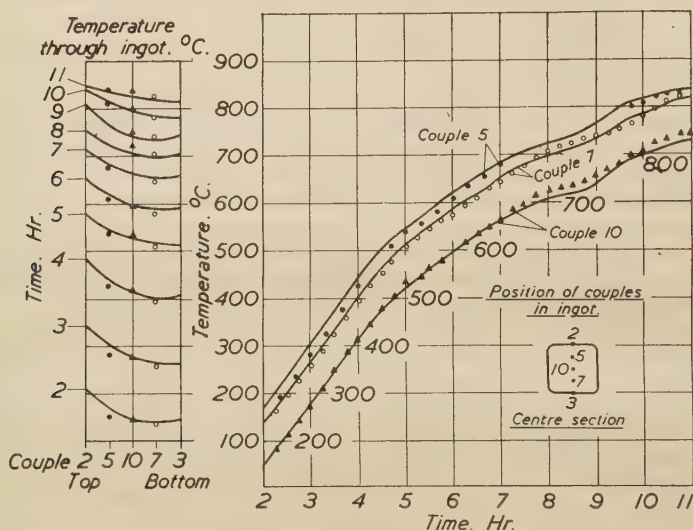
Fig. 21.—Asymmetrical Heating of 12-in. Square Ingot. Comparison of calculation and experiment.

Part 4.—Industrial Soaking Times.

§ 10.—Calculation by Nomograph and Slide Rule.

In order to make this work on heat flow of day-to-day use to the industrialist, a rapid means has been devised for obtaining the soaking time of steel under normal industrial conditions. The method, although approximate, will be found accurate enough for many purposes. The results can conveniently be obtained from either a nomograph or a special slide rule, details of which are given in Appendix C. It should be again emphasised, however, that the term " soaking time " mentioned here refers to the time required to reach a prescribed degree of temperature uniformity under conditions of heating which are uniform round the charge, and takes no account of that needed for any desired metallurgical changes which may occur, as, for example, in tempering.

Before discussing either method, however, it will be well to state a conclusion which has emerged in the course of this work.   It has become apparent that the soaking time is often more dependent on the furnace than it is on the steel itself.   In such case the use of the nomograph or slide rule will give misleading results as an indication of temperature uniformity within the charge.   Further, the discrepancy between the soaking time derived by calculation and the actual minimum soaking time found practicable in an existing furnace is a measure of the degree of improvement in soaking time which may be achieved by modification of the furnace design.

Further, it should be remembered that the temperature normally recorded as the surface temperature is obtained by a sheathed couple, placed somewhere in the furnace.   At the best this sheath rests on the stock, but often this is impracticable.   It follows, therefore, that there can be quite a wide divergence during heating up between the readings of this couple and the true temperature of the steel surface.   The results recorded in Fig. 19 show that this divergence may easily be as much as $50°$ C.   All general calculations have to be based, of course, on the true surface temperature of the steel, because there is no general relation between the temperature of the couple and that of the steel, nor can there be when the conditions vary from furnace to furnace and even in some cases from heat to heat.

Some preliminary calculations of typical heating curves were made on the differential analyser.   The results showed that the soaking time was almost entirely dependent on four factors—first, the properties of the steel being heated; secondly, the size of the mass; thirdly, the final part of the heating curve; and, lastly, the degree of uniformity required at the end of the soaking period— and that the relation between the soaking time and these variables could be represented approximately by quite a simple formula, which was amenable to evaluation by a nomograph or special slide rule.   The many other possible factors, such as the initial part of the heating curve, were found to have surprisingly little effect; the reason for this is explained at the end of § 7.

Fortunately, the thermal properties of many steels have recently been determined by the National Physical Laboratory.[2]   In the present context the particular property required is the diffusivity. It was decided to simplify the calculation by limiting it to articles of square or circular section, as these cover the greater part of the practical problems, and, in any event, in nearly all cases of slabs or sheets the steel is comparatively thin and the soaking time is correspondingly small.   The size of the circular- or square-section masses is taken as the diameter or the side of the cross-section.

The effect of the shape of the heating curve has been studied at some length and it has been found that in normal operation the first part had little or no effect on the soaking time (*see* Appendix C).   It is sufficient to consider only the time to heat

through the last 100° C.—that is to say, if the steel is to be soaked at 1200° C., then the time required is that taken for the surface to rise from 1100° to 1200° C. It was also found that the form of the curve in this range is important, but it was impossible to obtain a simple formula covering a large number of such curves, so a typical one was selected. This problem is discussed more fully
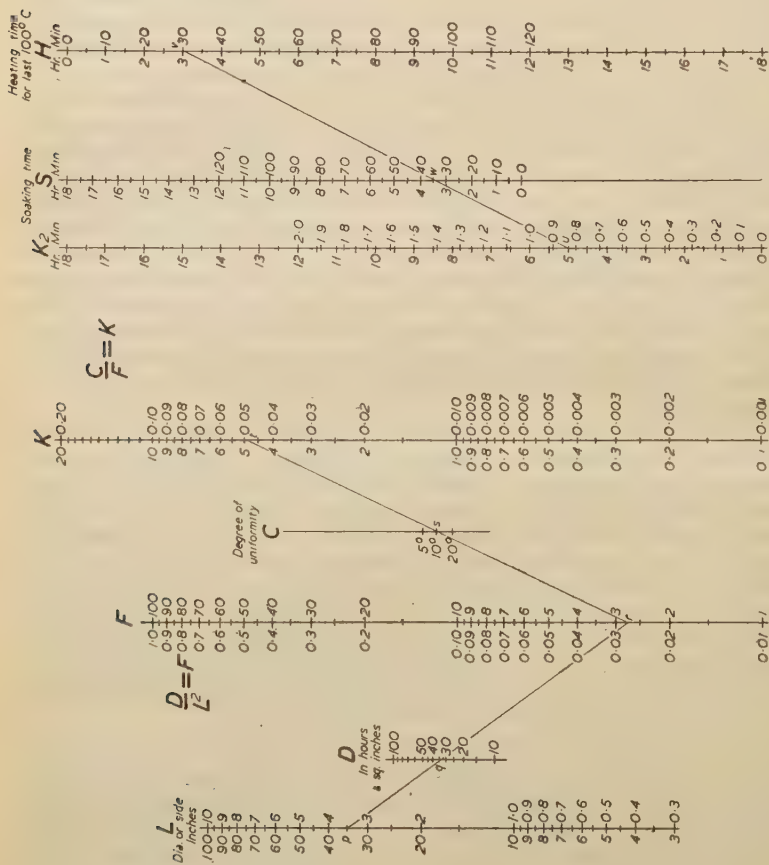
Fig. 22.—Nomograph for Calculating Soaking Times.

in Appendix C. The fact that the soaking times so found were in reasonable agreement with industrial practice where the heating conditions were applicable suggested that the curve selected was typical of a wide range of furnace-heating technique, and the simplification is therefore justified.

The degree of uniformity required represents the maximum difference of temperature between the inside and outside of the steel

mass at the end of the soaking period.   Three degrees of uniformity have been selected, the variation through the mass being 20°, 10° and 5° C.

Use of the Nomograph.

In using the nomograph, Fig. 22, the approximate composition of the steel and temperature of soaking are required.   These, in fact, fix the relevant thermal properties of the steel.   For the present purpose four steels have been selected which cover a wide range of industrial practice, and further steels can be added if required by the method given in Appendix C.   The reference numbers associated with the compositions in Tables IV. and V. are those given by the Thermal Treatment Sub-Committee.[2]

TABLE IV.—*Compositions of Steels.*

Steel No.	Approximate Analysis.				
	C. %.	Si. %.	Mn. %.	Cr. %.	Ni. %.
2	0·1	0·1	0·3	...	...
5	0·4	0·1	0·6	...	...
9	0·33	0·2	0·6	...	3·5
19	0·3	0·2	0·7	1·0	...

TABLE V.—*Diffusivities of Steels.*

Inch-hour units.

Temperature of Soak :	400° C.	600° C.	850° C.	950° C.	1200° C.
Steel No. 2 . .	54·0	36·0	23·0	27·4	30·2
No. 5 . .	50·4	33·8	32·7	36·7	42·1
No. 9 . .	46·8	34·2	30·2	29·9	32·8
No. 19 . .	45·4	32·4	25·5	40·3	45·0

Knowing the type of steel and the temperature of soaking, the appropriate diffusivity (D) can be found from Tables IV. and V. Refer now to the nomograph, Fig. 22.   Join the appropriate size of ingot or billet on the L scale, through the value of D just obtained, to meet the F scale.   Join this point through the degree of uniformity required, C scale, to meet the K scale.   Read off the value of K.   It is important in using this section of the nomograph that if the value of L is read on the left-hand scale the value of K shall also be read on the left-hand K scale.   Similarly, the right-hand scales of L and K should be worked together.

Turn now to the second part of the nomograph containing the three scales K_2, S and H.   Each of these scales is marked off in

minutes on the right and hours on the left.* On the more convenient of the K_2 scales read off the value of K already obtained.

Fig. 23.—Slide Rule for Calculating Soaking Times.

Join this point to the time for the last 100° C. read on the corresponding H scale. This line cuts the S scale to give the soaking time required. It is most important that if the value of K_2 is taken on the right-hand scale the values of H and S should also be referred to the minute scales; correspondingly, if the hour markings are more convenient all three values should be read in hours.

Example.—Consider the case of a 35-in. dia. ingot of 0·4% carbon steel which is to be soaked at 850° C. A degree of uniformity of temperature of 10° C. will suffice, and the surface has taken 3 hr. to heat from 750° to 850° C. From Table IV. the appropriate steel number is seen to be No. 5. Referring to Table V., the corresponding diffusivity, D, is found to be 33. Turning now to the nomograph, the size of the ingot, 35 in., is found on the left-hand L scale. This point (p) is joined through 33 on the D scale (point q) to meet the F scale in r. This point is joined through 10 degrees' uniformity on the C scale (s) to meet the K scale at a value of 5·0 read on the left-hand scale (point t). Choose the value of 5·0 on the left-hand K_2 scale marked " hours " (point u), join this point to the value 3 hr. on the left-hand H scale (v). This line cuts the S scale at w at a value of 3·5 hr. read on the left-hand scale. The ingot requires a soaking time of 3·5 hr.

The Slide Rule.

The principles underlying the slide rule are essentially similar to those of the nomograph, but by limiting the size of ingot to the range 7 in. to

* The heading of the K_2 scale has been marked in hours and minutes purely for reference, and not as an indication of the units employed.

100 in. it has been found possible to reduce the calculation to a form suitable for a special slide rule. The diffusivity of the steel cannot be calculated, but must be obtained from Tables IV. and V. in the same way as for the nomograph. For any particular purpose, however, these Tables will be quite small and can be printed on the back of the slide rule.

Use of the Slide Rule.—The rule, illustrated in Fig. 23, is used in the following way :

(i) From the Table find the diffusivity, D, corresponding to the steel composition and temperature of soaking.

(ii) Select this value on the " D " scale of the rule, and, using the cursor, not shown in Fig. 23, place in line with it the appropriate value on the " Degree of Soak " scale on the slide.

(iii) Referring to the " Dia. or Side " scale on the slide, select the appropriate size of ingot and read off the corresponding value of K on the lower " K " scale.

(iv) Place the cursor over the same value, but read on the " Time of Soak " scale.

(v) Place the zero of the " Time for the Last $100°$ C." scale under the cursor.

(vi) Opposite the appropriate time for the last $100°$ C. read off the " Time of Soak."

Conclusions.

This work has shown that the technique which had been devised for the calculation of heat flow in the unsteady state has proved to be capable of practical application with a high degree of accuracy. It will take account of any form of heating or cooling curve. Although based fundamentally on an approximation, the method has proved to be more accurate than the data on the thermal properties of the material which are necessary for its application. It has been found practicable to include both the variation of diffusivity with temperature and the latent heat at a change point. Further properties, such as the latent heat of fusion and the dependence of the rate of transformation on temperature and on the degree to which the transformation has proceeded, could be taken into account if sufficient quantitative data on these properties were available. The application of the method is simplest when the variation of the surface temperature with time is given, but it can be extended to apply when the surface condition is a given rate of surface heat transfer or a given relation between this surface heat transfer and the surface temperature; in these cases the time variation of the surface temperature is one of the results of the calculation.

Further, it has been found practicable to extend the method to the calculation of the cooling of an ingot in a mould, including the

different thermal properties of the two materials and the radiative heat transfer across the air gap between them. The results showed good agreement with temperature measurements made during the casting of 9-in. and 11-in. ingots.

An important result of the comparison of calculations with measurements both in the laboratory and in typical works furnaces is the emphasis that it has laid on the need for improved technique in the measurement of temperatures in masses of steel under non-steady conditions. It has shown the desirability of at least a rough check between results of observation and calculation, if the latter can be made, before the former are accepted; the technique developed in the present work provides a means of making such calculations. On one occasion a comparison of calculated results with those experimentally determined led to suspicion of the observations, which otherwise would have been accepted without question, but which were found, after further experimental work, to be erroneous.

A rapid method of calculating the centre temperature of a steel mass during heating, the " time-lag " method, has been shown to be more accurate than was at first expected, and quite adequate for many practical purposes. A nomograph and slide rule have been devised to calculate the soaking time of steel in industrial furnaces. They can be made to allow for various types of steel as well as for the different degrees of uniformity of temperature required in different processes.

A general conclusion of great practical interest is that the true soaking time for the steel is shorter than that normally allowed in industrial practice. This appears to be due to the fact that the soaking time in practice is dependent more on the time taken for the furnace to reach a uniform temperature than on the true soaking time of the steel itself. This leads to the further conclusion that more attention should be paid to the way in which the heat is put into a furnace, so that lack of uniformity of heating is reduced to a minimum.

Finally, it has been found that the range of problems to which it is possible to apply the method of calculating variable heat flow is at present limited, in some directions, not by restrictions imposed by the technique of making the calculation but by incompleteness of the thermal data on which such a calculation has to be based. The method would be capable of wide extension if the necessary quantitative data were available, and it is hoped that the development of a method which could use such data will be a stimulus to further work on their determination.

authors also gratefully acknowledge the assistance which has been received from the National Physical Laboratory who have supplied them with much valuable data on the physical properties of steels.

The electrical computor described in this work was built in collaboration with the Metropolitan-Vickers Electrical Co., Ltd., and the authors wish to thank them, and Dr. R. W. Sillars in particular, for their co-operation.

They are also indebted to the Ministry of Supply for permission for their differential analyser group at Manchester University to assist in this work, and to Mr. J. Howlett and Mrs. P. Nicolson for contributions to the work at various points.

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APPENDIX A.—*The Differential Analyser and its Application to the Heat-Flow Equations.*

Several accounts of the differential analyser have already been published,[5] which include some details of the way a differential equation is presented to it for solution and how it is operated so as to produce solutions, but to make the present paper self-contained, a short account of the machine and its application to the heat-flow equation is given here.
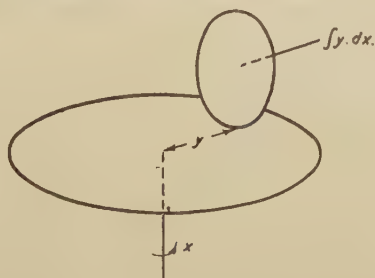
Fig. 24.—Form of Gear in Differential Analyser.

The fundamental units of the machine are the integrators, each of which is a precision form of continuously variable gear. Any mechanism by which the gear ratio between two shafts can be varied continuously and while the shafts are rotating can be used as an integrating mechanism; the particular form of gear used for the purpose in the differential analyser consists of a horizontal disc driving a vertical wheel (*see* Fig. 24), the plane of the wheel being

fixed and the vertical axis about which the disc can rotate being supported in bearings in a movable carriage, so that the distance from the centre of the disc to the point of contact of the wheel with it can be varied. To evaluate an integral, say, $\int y\,dx$, the lead screw controlling the position of the movable carriage is driven by the shaft the rotation * of which represents y, and the disc is rotated by a second shaft the rotation of which represents x.

Only a small torque can be taken from this friction drive without vitiating the accuracy of the evaluation of the integral. On the other hand, in the interconnections between the integrators required for the evaluation of the solution of a differential equation a considerable load may have to be driven by the output from an integrator. To enable this to be done, the integrating wheel drives the output shaft through a high-ratio mechanical " servo " or " torque amplifier," which steps up the output torque by a factor of the order of 8000.

An input table consists of a drawing board spanned by a bridge movable in a direction perpendicular to its length; the bridge supports a carriage which can be moved along its length by the rotation of a handle and which carries a pointer. A graph, previously drawn and representing the information to be supplied to the machine, is placed on the drawing board. The bridge is traversed across the graph by the operation of the machine, and, as it so moves, an operator turns the handle so as to keep the pointer on the curve. A drive is also taken from the handle to that shaft of the machine to which the information expressed by the curve is to be supplied, for example, the shaft driving the lead screw of an integrator. The output table is similar, but the pointer is replaced by a pencil driven in both co-ordinates by the machine; an adding unit is an ordinary differential gear; constant multipliers and scale factors are introduced by spur gear trains.

The shafts and gearing by which the units of the machine are interconnected can be assembled in different ways, and form a very adaptable gearbox with a large number of possible combinations. A differential equation is presented to the machine by setting up the appropriate mechanical connections in this gearbox. The shafts which directly drive or are driven by the integrators, input tables and output table lie across the length of the machine, and are geared to longitudinal shafts by means of helical gears; the longitudinal shafts are geared together, where required, through spur gears and adding units. The longitudinal shafts are on a different level from the cross shafts, and any one of the cross shafts can be connected to any one of the longitudinal shafts; the extent of the range of equations to which the machine can be applied depends on the freedom of interconnection between the different units which is thus provided. The accuracy of the machine itself is ample for the present application.

* " Rotation " here means *total* rotation in shaft turns, not angular velocity of rotation.

Consider, now, the application of the differential analyser to the equations of heat flow in the approximate forms (3) or (5), and first consider particularly, as an example, the case of heat flow in a slab for a given time variation of surface temperature, the diffusivity being independent of temperature.

To see how to apply the machine, it is most convenient to consider the equation (3) formally integrated with respect to t; if the diffusivity is constant and equal to D, this gives :

$$\theta_Q = [D/(\delta x)^2] \int (\theta_R - 2\theta_Q + \theta_P) dt \quad . \quad . \quad . \quad (10)$$

and there is a similar equation for each of the points P, Q, R....

The factor $D/(\delta x)^2$ can be taken into the time scale. One integrator is required to evaluate the integral in equation (10) for each of the points P, Q, R....; consider that integrator which evaluates θ_Q. The integrand $(\theta_R - 2\theta_Q + \theta_P)$ in this integral is constructed by adding units from θ_Q, which is the output of this integrator itself, and from θ_P and θ_R, which are the outputs of two other integrators, except when Q is one layer within the surface, when one or other of θ_P and θ_R will be the surface temperature, which, being specified as a function of time, is supplied from an input table. The time variation of the internal temperature can be recorded graphically on the output table or numerically by counter readings.

When the diffusivity varies with the temperature there are several ways of taking this variation into account. One method is as follows : Formal integration of equation (3) with respect to t now gives :

$$\theta_Q = [1/(\delta x)^2] \int [D(\theta_Q)](\theta_R - 2\theta_Q + \theta_P) dt \quad . \quad . \quad . \quad (11)$$

and similarly for the other points P, R...., and now the factor $D(\theta)$ is both different for each of the points P, Q, R...., and varying with time as the temperature at each of these points varies.

Now, it is possible to connect two integrators so that they evaluate the integral of a product currently from its factors. This can be used to evaluate the integrals like (11) for the temperatures at each of the points P, Q, R. For the point Q the integrand is the product of two factors, one, namely, $D(\theta_Q)$, being supplied from an input table as the machine evaluates θ_Q, and the other, namely, $(\theta_P - 2\theta_Q + \theta_R)$, being constructed by adding units from the outputs of three integrators evaluating θ_P, θ_Q, θ_R, as before.

This method requires an input table for each point P, Q, R...., since for each of these points the diffusivity has to be supplied to the machine continuously as the temperature varies. Further, it requires two integrators for each point P, Q, R, and in this respect it makes considerable demands on machine capacity.

As mentioned in the text (end of § 3), it may often be an adequate approximation to regard the diffusivity as uniform through the material at any moment, although it is not an adequate approximation to neglect its variation over the temperature range covered by the material in the course of time.

This can be expressed by replacing $D(\theta_Q)$ in equation (11) by $D(\bar{\theta})$, where $\bar{\theta}$ is a suitable mean temperature through the material, and is taken to be the same in all the integrals like (11) for the various points P, Q, R . . . . This is equivalent to working on a distorted time scale in which the measure of a small interval of time dt, when the mean temperature is $\bar{\theta}$, is proportional to $D(\bar{\theta})dt$. One input table and one integrator are required to produce the relation between this distorted time scale and the scale of time t, in terms of which the variation of surface temperature is given. For conditions under which this approximation can be expected to be a good one, the best temperature to take for the mean temperature $\bar{\theta}$ is, for a plane slab symmetrically heated, one-third of the way from the central temperature to the surface temperature, and, for a cylinder symmetrically heated, the arithmetic mean of these temperatures. This method has been used in most of the work for which results are given in this paper.

The approximate equations (5) and (6) for radial heat flow in a cylinder can be dealt with in a similar manner, and, by a slight extension, surface conditions in the form of a given surface heat transfer or given relation between surface heat transfer and surface temperature can be handled. It can also be extended to inhomogeneous materials, such as a slab formed by two sheets of different materials in contact, the heat-flow conditions across the surface of contact being that both the temperature and the heat transfer are the same for both materials. A less simple situation has been treated in the cooling of an ingot in a mould (§ 8), in which the heat transfer between the outside of the ingot and the inside of the mould wall takes place by radiation and depends on the temperatures of these two surfaces according to Stefan's law.

The abnormal thermal properties in the neighbourhood of the change point can also be taken into account, at least approximately, in this treatment of heat flow, and in more ways than one.

In one method, the one which has been most used in the present work, a smooth specific-heat curve, omitting the peak, is drawn through the temperature range in which the thermal properties are abnormal (say, 700–750° C. in the case of steel No. 5[(2)]) and integrated, and the change in total heat over this temperature range which is not thereby included is regarded as latent heat absorbed or emitted at a single " transformation temperature " (taken as 715° C. for steel No. 5). An approximate treatment of this situation can be included in the solution of the heat-flow equations on the differential analyser.

If the transformation took place strictly at a fixed temperature, with absorption and emission of latent heat, it would at any moment be taking place on a surface within the material, not throughout a volume; but in the present treatment, in which the material is thought of as divided up into a finite number of layers, it is easiest to regard the transformation as taking place layer by layer; this

will not give correct results for the details of the heat flow in portions of the material at temperatures in the immediate neighbourhood of the transition temperature, but should give approximately the right net heat balance between this and other portions of the material.

APPENDIX B.—*The Electrical Computor and its Application.*

(a) *Determination of the Relations Between Resistances, Capacities and Time Scales.*

The electrical computor is based on an analogy, not with the exact equations of heat flow, but with an approximate form thereof, and the appropriate values for the resistances, capacities and voltages in the circuit can best be derived from a comparison of the sets of equations appropriate to the two systems. Although only three simple cases, linear heat flow in a slab, radial flow in a cylinder and two-dimensional flow in a square prism, are considered here, it will be clear that the scope of an instrument of this kind is much wider. It will be assumed in the present section that the diffusivity is constant; the extension of the results to a diffusivity uniform at each moment but varying in the course of time, will be discussed later, in section (d) of this Appendix.
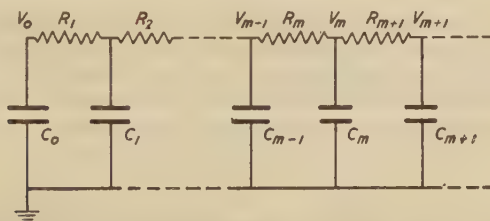
FIG. 25.—Ladder Network.

In the ladder network shown in Fig. 25, the series resistances have values $R_1, R_2 \ldots$, in general, $R_m = 1/S_m$; the shunt capacities have values $C_1, C_2 \ldots$, in general, C_m; and V_m is the potential difference across C_m. From the equation relating the currents through the resistances and condensers and the voltages across them, it follows that the voltages across any three successive condensers are related by :

$$S_{m+1}V_{m+1} - \left(S_m + S_{m+1} + C_m \frac{d}{dT} \right)V_m + S_m V_{m-1} = 0, \quad (12)$$

where T is the measure of time for transient phenomena in the network.

In treating symmetrical heat flow in a slab or cylinder it is convenient to terminate the network in a capacity C_0 representing

the central plane of the slab or axis of the cylinder. The potential V_0 across it is given by :

$$SV_1 - \left(S + C_0 \frac{d}{dT} \right) V_0 = 0. \quad . \quad . \quad . \quad . \quad (13)$$

(i) *Linear Heat Flow in a Slab.*—If, for linear heat flow in a slab, θ_m is written for the temperature at a plane at $m\delta x$ from the central plane of the slab (or from some other convenient zero), the approximate equation of heat flow (3) can be written :

$$\theta_{m+1} - \left[2 + \frac{(\delta x)^2}{D} \cdot \frac{d}{dt} \right] \theta_m + \theta_{m-1} = 0. \quad . \quad . \quad (14)$$

Equations (12) and (14) are equivalent if :

$$\frac{S_{m+1}}{1} = \frac{S_m + S_{m+1}}{2} = \frac{C_m D}{(\delta x)^2} \cdot \frac{t}{T} = \frac{S_m}{1}. \quad . \quad . \quad . \quad (15)$$

The two equalities involving the resistances are consistent, and are satisfied by making all the resistances equal, say, of value R (and not otherwise). Then, from the remaining equality in equation (15) it follows that all the capacities must be equal—say, of value C—and that the ratio of the time scales in the electrical computor and in the heat flow is given by :

$$\frac{T}{t} = \frac{CRD}{(\delta x)^2}. \quad . \quad . \quad . \quad . \quad . \quad (16)$$

Thus, any convenient values of C and R can be chosen, and then (for a given material, dimensions, and numbers of layers into which it is divided) the ratio of the time scales is determined.

For symmetrical heat flow in a slab, the equation for the central temperature is equation (4), which can be written :

$$\theta_1 - \left[1 + \frac{(\delta x)^2}{2D} \cdot \frac{d}{dt} \right] \theta_0 = 0. \quad . \quad . \quad . \quad . \quad (17)$$

If a network terminated by a condenser C_0 (corresponding to the central plane of the slab) is used for this case, it follows from a comparison of equations (13) and (17) that :

$$\frac{S_1}{1} = \left[\frac{2C_0 \cdot D}{(\delta x)^2} \right] \frac{t}{T},$$

and so that :

$$C_0 = \tfrac{1}{2}C. \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

(ii) *Radial Heat Flow in a Solid Cylinder.*—If, in radial heat flow in a solid cylinder, θ_m is written for the temperature at radius $m\delta r$, then from equation (6) it follows that :

$$(2m + 1)\theta_{m+1} - \left[4m + \frac{2m(\delta r)^2}{D} \cdot \frac{d}{dt} \right] \theta_m + (2m - 1)\theta_{m-1} = 0 \quad . \quad (19)$$

for $m > 0$; and from equation (7) :

$$\theta_1 - \left[1 + \frac{(\delta r)^2}{4D} \cdot \frac{d}{dt} \right] \theta_0 = 0 \quad . \quad . \quad . \quad . \quad (20)$$

for the central temperature. Equations (12) and (13) are equivalent to equations (19) and (20) if :

$$\frac{S_{m+1}}{2m+1} = \frac{S_m + S_{m+1}}{4m} = \frac{C_m D}{2m(\delta r)^2} \cdot \frac{t}{T} = \frac{S_m}{2m-1}. \quad \cdot \quad \cdot \quad (21)$$

The equalities involving the resistances are consistent, and are satisfied if :

$$S_m = \frac{2m-1}{R},$$

where R is an arbitrary resistance independent of m. Hence, for a solid cylinder the successive resistances must be in the ratio :

$$R_1 : R_2 : R_3 : \ldots = 1 : \tfrac{1}{3} : \tfrac{1}{5} : \ldots$$

The other equality then shows that the capacities C_m (other than C_0) must be in the ratio :

$$C_1 : C_2 : C_3 : \ldots = 1 : 2 : 3 : \ldots$$

or, generally :

$$C_m = mC \quad (m > 0), . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

where C is arbitrary, and that the time scales are then related by :

$$\frac{T}{t} = \frac{CRD}{2(\delta r)^2}.$$

Since $R_1 = R$, and $C_1 = C$, this can be written alternatively as :

$$\frac{T}{t} = \frac{C_1 R_1 D}{2(\delta r)^2}. \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

To find the appropriate value of C_0, compare equations (13) and (20); these are equivalent if :

$$\frac{S_1}{1} = \left[\frac{4DC_0}{(\delta r)^2}\right] \frac{t}{T},$$

and comparison with equation (23) then gives :

$$C_0 = \frac{C_1}{8}. \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

(iii) *Square Prism.*—Treatment of the heat flow in two dimensions, without the symmetry of radial heat flow in a cylinder, by an electrical computor requires a two-dimensional net of resistances with all the mesh points earthed through capacities (*see* Fig. 26).

Let θ_P be the temperature at a mesh point P of a square-mesh grid in the material in which the heat flow is taking place, $\overline{\theta}_P$ the mean of the temperatures at the four mesh points nearest to P,

and δs the side of the mesh. The use of the approximation (2) for both the x and y derivatives in the heat-flow equation :

$$\frac{\partial \theta}{\partial t} = D\left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2}\right)$$

gives :

$$\frac{\partial \theta}{\partial t} = \frac{4D(\bar{\theta} - \theta)}{(\delta s)^2}. \qquad . \qquad . \qquad . \qquad . \qquad . \qquad . \qquad (25)$$

In the network shown in Fig. 26 all the resistances have the same
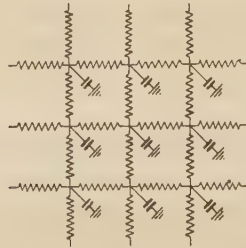
FIG. 26.—Net of Resistances for Treatment of Heat Flow in Two Dimensions in the Electrical Computor.

value, R, and all the capacities the same value, C; V_P is the potential at any mesh point P, and $\bar{V}_P$ the mean of the potentials at the four nearest neighbouring mesh points. Then :

$$\frac{\partial V_P}{\partial T} = \frac{4(\bar{V}_P - V_P)}{CR}. \qquad . \qquad . \qquad . \qquad . \qquad . \qquad (26)$$

These equations are equivalent if $V_P = a\theta$, where a is arbitrary, and :

$$\frac{T}{t} = \frac{CRD}{(\delta s)^2}. \qquad . \qquad . \qquad . \qquad . \qquad . \qquad . \qquad (27)$$

(compare equation (16)).

For heat flow in a plane normal to the length of a prism the section of which is a square, or a rectangle the sides of which are in the ratio of reasonably small integers, all surfaces can be made grid lines by a suitable choice of δs and the application of surface conditions presents no difficulty ; it is not necessary that the temperature should be uniform all round the surface. A similar treatment can be applied to heat flow in three dimensions.

(b) *Construction of an Experimental Version of an Electrical Computor.*

An experimental model of an electrical computor has been built as mentioned in the text (§ 4) and illustrated in Figs. 5, 6 and 27. This model and its testing and operation will be described somewhat

more fully than the differential analyser, since, in contrast to that machine, it has not been previously described.

(i) *The Circuit.*—The circuit consists of a number of resistances and capacities, the numbers and values of the various components depending on the problem to be solved. For evaluating heat flow through a slab, for example, the resistances have to be all equal, and the capacities all equal, except that for a symmetrically heated slab the capacity of the condenser representing the centre of the slab has to be half that of the others (*see* section (*a*)(i) above). As already explained in the text, the use of manual methods for supplying a time-varying voltage corresponding to a given time variation of surface temperature, and for recording the result, calls for high resistances and large capacities with small leakage.
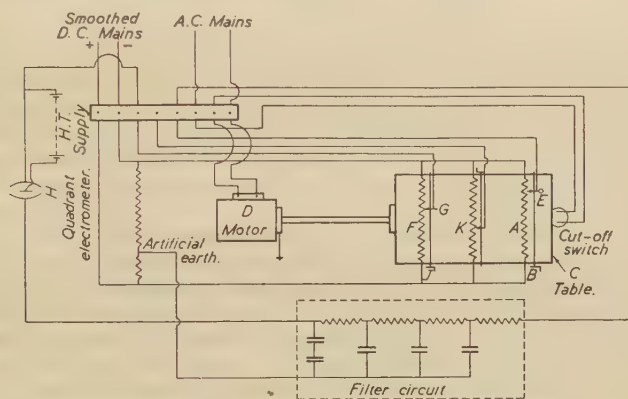
Fig. 27.—Circuit Diagram of Electrical Computor.

In the instrument here described, four sections of the circuit were used, employing condensers of 7·1 microfarads capacity and resistances having a value of 1 megohm. Under these conditions, the most rapid operation corresponding to an instantaneous heating of the surface was virtually completed in 2–3 min. This rate of operation is near the limit at which manual control is accurate. The condensers are such that the leakage resistance across the circuit is greater than 500 megohms, and under these conditions the potential drop due to leakage over a period of a quarter of an hour is less than 0·5%.

(ii) *The Input Unit.*—The input potentiometer A consists of a straight wire-wound resistance having a value of 800 ohms, along which a slider can be moved by a lead screw operated by the handle B. The given time-temperature curve is drawn on the end of table C, which is moved at 0·64 in. per min. by the synchronous motor D. As the table moves under the potentiometer the bull's eye E attached to the slider is maintained on the input curve by rotating handle B,

the corresponding time-voltage curve being thus fed into the machine.

The potentiometer K, Fig. 27, was included in the model to deal with problems in which two separate time-temperature input curves were known. This resistance would be used, for example, if a slab heated non-uniformly from the two sides were being considered.

(iii) *The Output Unit.*—The output voltage of the circuit is measured by balancing it against a known voltage by means of a null-deflection method.

As a result of the high resistances used in the filter circuit the currents flowing through it will be very small, of the order of micro-amperes, and hence the voltage-measuring device for the output mechanism must be one requiring a vanishingly small working current. In the earliest trials of this machine a cathode-ray oscillograph was used as a null-deflection instrument to measure the output, but it was found that sufficient space charge was picked up on the deflector plates from the electron beam to interfere with the output potential. When it was replaced by a quadrant electrometer requiring no current the measurement was satisfactory. It was also found desirable to connect the high-tension battery from the quadrant electrometer needle to the pair of quadrants connected to the potentiometer.

The output potentiometer F is similar to the input unit, except that the bull's eye is replaced by the pen mechanism G. The slider is connected to one side of the quadrant electrometer H, the other side of which leads to the point of the filter circuit at which the potential is required. By rotating the handle J, the pen G and its slider are moved so that a potential is applied to the quadrant electrometer to balance that existing in the ladder circuit. Thus, the movement of the pen G over the table C corresponds to the time-potential curve of the output of the circuit. The time-temperature curve at the required point in the steel can therefore be obtained.

In order to overcome the end effects of both the input and output potentiometer resistances, two resistances of 1800 and 80 ohms were connected in series across the D.C. mains, and their common connection was used as an artificial earth for the ladder circuit.

(c) *Tests.*

In order to test the accuracy of the computor, it was checked in a number of problems in which the formal mathematical solution could be evaluated. Two cases are here selected, the instantaneous surface heating, and that in which the surface temperature obeys the equation :

$$\theta_S = \tfrac{1}{3}[50 - e^{-t/5}(t^2 + 10t + 50)], \quad . \quad . \quad . \quad (28)$$

in which θ_S = surface temperature.
                 t = time.
                 e = base of natural logarithms.

The simplest way to demonstrate the accuracy of the machine is to compare the times at which various temperatures are attained. Such a comparison for the instantaneous heating is given in Table VI.

TABLE VI.—*Results of Instantaneous Heating.*

| Ratio of Centre Temp. to Surface Temp. (1) | Time.   Arbitrary Units. | | Percentage Error. (4) | Percentage Error with Adjusted Zero. (5) |
	Calculated. (2)	From Machine. (3)		
0·410	11·2	11·6	3·57	0
0·730	22·7	23·2	2·20	+0·44
0·870	34·3	34·8	1·46	+0·29
0·943	46·0	46·4	0·87	0
0·988	69·2	69·5	0·44	−0·14

It can be seen that the results (column (4)) are correct to an accuracy of approximately 1% except in those cases where the times were small. It is realised that the machine was built as a trial model to demonstrate the method, and the accuracy of measurement alone is only of the order of 1%, while other mechanical and electrical errors may arise. The errors shown in Table VI., column (4), are obviously systematic, and a movement of the zero on the actual chart obtained by a distance of 0·3 mm., which is reasonable, would give the figures in column (5), which suggests that with refinements the machine would give the correct result.

This instantaneous heating is never met with in practice, and therefore a second heating curve was used more nearly approaching those found in industrial practice, namely, the solution to the case in which the surface temperature obeys equation (28).

The results are shown in Table VII. and compared with the

TABLE VII.—*Results of Second Heating Curve.*

| Ratio of Centre Temp. to Max. Temp. | Time.   Arbitrary Units. | | | Percentage Error. | |
| | Calculated. | From Machine. | | | |
		Charge.	Discharge.	Charge.	Discharge.
0·121	16	16·7	16·2	4·4	1·2$_5$
0·564	32	33·5	32·4	4·7	1·2$_5$
0·860	50	52·4	50·8	4·8	1·6

calculations. Two sets of values—charge and discharge—are recorded. The first set of results was obtained by building up a potential on the network corresponding to the temperature rise. This is the more obvious and simple method of working, but,

unfortunately, any errors due to leakage or soakage occurring in the condensers reach their maximum effect when the potential is greatest, resulting in appreciable errors in the results obtained.   It was therefore decided to charge the condensers at the start of the experiment and decrease the voltages to correspond to temperature rise.   By this means the effect of these faults of the equipment should be reduced to a minimum.   That this was the case is shown in Table VII., the error being decreased from approximately $4\cdot5\%$ to $1\cdot3\%$.

From these two experiments it is concluded that the basic principles of the machine are satisfactory, and the inaccuracies are due to the experimental character of the machine and, in particular, to the shortcomings of the electrical equipment, which had to be selected from material readily to hand.   These defects became more serious when complex shapes, such as the cylinder, were studied. This matter is now under investigation.

(d) *Variable Diffusivity.*

In considering the application of the electrical computor to heat flow with variable diffusivity, it will be assumed that it is an adequate approximation to take the diffusivity as uniform through the material at each instant, though varying with time.

Then the greater part of the discussion of section (a) of this Appendix stands, with D replaced by $D(\bar{\theta})$, where $\bar{\theta}$ is some mean temperature through the material.   The only differences are that in the treatment of the slab Dt/T in equation (15) must be replaced by $D(\bar{\theta})dt/dT$, and equation (16) becomes :

$$\frac{dT}{dt} = \frac{CRD(\bar{\theta})}{(\delta x)^2}, \qquad . \qquad . \qquad . \qquad . \qquad . \qquad . \qquad (29)$$

and similarly in the treatment of the cylinder and square prism.

Equation (29) shows that (to the approximation specified) the varying diffusivity can be expressed by a distortion of the time scale of the computor relative to that of the heat flow.   Practical application of this involves two points, the determination of the appropriate mean temperature $\bar{\theta}$ and the means of introducing the appropriate distortion of the time scale when supplying to the computor the variation of surface temperature with time.   Both can be dealt with in several ways.

Considering first the determination of $\bar{\theta}$, the diffusivity does not vary rapidly with temperature, and although the surface temperature will usually be the upper or lower limit of the range of temperature in the material at any moment, it may be an adequate approximation to take $D(\theta_S)$ for $D(\bar{\theta})$; this, at any rate, will give a better approximation than taking D as constant.   Alternatively, the " time-lag " solution of § 5 could be used to estimate the time variation of the central temperature, and a mean temperature

obtained from this and the surface temperature would almost certainly be an adequate approximation to $\bar{\theta}$ in cases where the use of a uniform $D(\bar{\theta})$ is itself an adequate approximation. Another possibility is to use the method of successive approximation, first replacing $D(\bar{\theta})$ by $D(\theta_S)$, then using the solution to give a better approximation to θ, and repeating the solution with successively better approximations to θ as often as necessary; actually one repetition would probably be adequate in practice. Another possibility is to construct θ currently from θ_S and θ_0, as the former is fed into the computor and the latter determined by the operation of the output unit.

If the distortion of the time scale to be used is known before the process of calculating the solution is started, as in the first three methods indicated in the previous paragraph, then it can be introduced by drawing the input curve for the computor on the distorted time scale given by integration of equation (29), namely :

$$T = \left[\frac{CR}{(\delta x)^2}\right] \int D(\bar{\theta}) dt. \quad . \quad . \quad . \quad . \quad . \quad (30)$$

The output curve would then be drawn on the same distorted time scale, and would have to be read off and redrawn to show the temperature variation on a uniform time scale for the heat flow.

This use of distorted time scales for the input and output curves could be avoided if the drive for the motor D to the tables were taken through a continuously variable gear (similar in design, perhaps, to an integrator of the differential analyser), by which the T scale of time on which the computor operates could be transformed into a uniform t scale of input and output curves.

APPENDIX C.—*Basis of the Nomograph and Slide Rule.*

In carrying out calculations which shall be applicable to all sizes of stock and all types of steel it is an advantage to replace the normal time-temperature curve by a relation between temperature and a non-dimensional measure of time.

This measure, which will be referred to as the " reduced time," is :

$$\frac{Dt}{L^2},$$

where t = time in hours.
D = diffusivity in inch-hour units.
L = diameter or side of mass in inches.

Preliminary machine calculations on typical heating curves showed that only the last 100° C. of the heating curve has an appreciable effect on the soaking time required, provided that the previous rate of heating is less than 1800° C. per unit of " reduced time." For a 10-in. dia. bloom of steel No. 5 (diffusivity as given in Table

V.) this rate of heating is 750° C. per hr. For a 50-in. ingot the corresponding rate is 30° C. per hr.

For the present purpose, to obtain a family of curves which should be mathematically similar and also closely represent the heating curves obtained in practice a series of parabolas was used to cover the last 100° C. range in a series of reduced times (τ).

The calculated relations between the " reduced time for the last
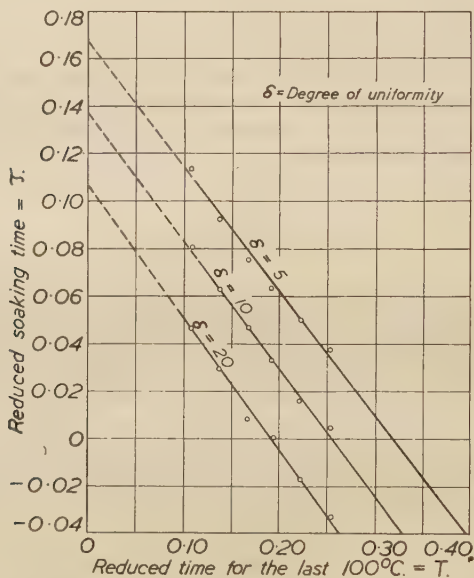
FIG. 28.—Relation between " Reduced Time for last 100° C." (T), and " Reduced Soaking Time " (τ).

100° C." (T) and the " reduced soaking time " (τ) for three values of uniformity of soaking are given in Fig. 28. In each case a straight line can be drawn through the points, and these lines are parallel.

The lines can therefore be represented by the equation :

$$\tau = -mT + C, \quad . \quad . \quad . \quad . \quad . \quad . \quad (31)$$

where m is a constant for all curves and C varies with the degree of uniformity. If the actual soaking time in hours is S and the heating time for the last 100° C. is H, then equation (31) can be rewritten :

$$\frac{S \cdot D}{L^2} = -m \frac{H \cdot D}{L^2} + C, \quad . \quad . \quad . \quad . \quad (32)$$

$$i.e., \ S = -mH + \frac{CL^2}{D} \quad . \quad . \quad . \quad . \quad (33)$$

The Nomograph.

The nomograph is constructed in two sections; the first gives the value $CL^2/D(= K)$ and the second section performs the operation $S = - mH + K$.

In the construction of the nomograph, the scales L and F are logarithmic with the same linear units. The scale D is also logarithmic to one-third the linear dimensions and is positioned so that $LD = \frac{1}{2}DF$. The 10 on the D scale is fixed on a line joining the 10 on the left-hand L scale to the 0·1 on the left-hand K scale. In this way $F = D/L^2$. In a similar manner the calculation $K = C/F = CL^2/D$ is made. The scales F and K are logarithmic with the same linear units. The scale C is midway between them, and divided logarithmically but to half the linear dimensions. The points corresponding to 5°, 10°, 20° of uniformity are marked off to agree with the values 0·168, 0·138, 0·107, respectively, obtained from Fig. 28. The 1·0 of the C scale is fixed on a line joining the 0·1 on the F scale to 10 on the K scale. In this way $C/F = K$.

In the second half of the nomograph the scales are linear, that of K being marked upwards and that of H downwards to the same dimensions. The centre scale S is to half the scale of the others and is marked upwards. Its position is such that the $\dfrac{\text{distance } KS}{\text{distance } SH} = m = \dfrac{45}{84}$. This is the value obtained from Fig. 28. The zero of S is fixed on a line joining the zeros of K and H. In this way $S = - mH + K$ obtained from the second section of the nomograph, $= - mH + CL^2/D$ from the first section of the nomograph.

The Slide Rule.

The equation to be solved is $S = - mH + CL^2/D$. The values of D have been summarised in Table V.

The first step in the slide-rule method is the calculation of $CL^2/D \ (= K)$. Now :

$$\text{Log } K = \log C + 2 \log L - \log D. \quad . \quad . \quad . \quad (34)$$

The calculation can be carried out by normal slide-rule practice. Equation (34) can, however, be rewritten in the form :

$$\text{Log } K + \log D = \log C + 2 \log L. \quad . \quad . \quad . \quad (35)$$

The addition of the logarithms is easily carried out by placing the two scales $\log K$ and $\log D$, or $\log C$ and $2 \log L$, in opposite directions with a common zero, as shown in Fig. 29.

Now, in Fig. 29 the two distances between the arrows are equal by equation (35). Hence, knowing three of the values C, L, D, K, the fourth can be found by placing the two sets of scales together so that one end of the ranges denoted by the arrows is common, in which case the other end is known and the required value can be read off. In practice the values on the D and C scales are placed together and the known value of L is opposite the value of K required.

For convenience in the construction of a practical slide rule the base of the C scale has been moved to the left to allow of extension of the diameter or side scale down to 7. The D scale has therefore also been moved to the left by the same amount. In addition, the logarithmic markings of the C scale have been replaced by 5°, 10°
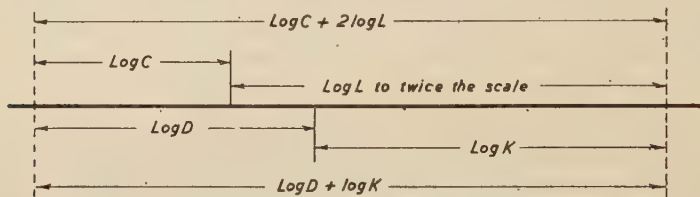
FIG. 29.—Illustration of the Principle Used in the Slide Rule.

and 20° marks at the appropriate places of 0·168, 0·138 and 0·107. The D scale has also been offset from the K scale to avoid confusion.

Equation (33) can be rewritten in the form $S = -mH + K$. This calculation is carried out on the upper part of the rule. The value of K previously obtained is found on the top linear scale. By moving to the left by an amount mH, the value S is reached on the same scale. As m is 45/84 from Fig. 28, the scale of H is marked in units which are 45/84 times the size of the K and S units. This scale is, of course, marked from right to left and is included on the slide of the rule.

Hence, knowing D, C and L, the value K $(= CL^2/D)$ is found, and, knowing K, H and m, the value S $(= -mH + K)$ is obtained.

The Scales of the Slide Rule.

For convenience the types of scale are here summarised.

(i) *Time of Soak and Upper* K *Scale.*—This is linear and reads from left to right.

(ii) *Time for Last* 100° *C.*—A linear scale of unit only 45/84 times that of the upper K scale. The scale reads from right to left and is on the slide of the rule.

(iii) *Degree of Soak.*—A logarithmic scale marked on the slide, reading from right to left, with only the values corresponding to 5°, 10° and 20° included.

(iv) *Diameter or Side.*—A logarithmic scale, reading from left to right, of twice the unit size of the degree-of-soak scale.

(v) *Lower* K *Scale.*—Logarithmic, to the same scale as the degree of soak, and reading from left to right.

(vi) D *Scale.*—Logarithmic, to the same scale as the degree of soak, reading from right to left, offset from the lower K scale and displaced to the left by an amount corresponding to the distance 7 to 10 on the diameter or side scale.

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CORRESPONDENCE.

Mr. VICTOR PASCHKIS (Columbia University, New York, U.S.A.) wrote : The work of the authors should be highly commended. The comparison between results obtained by direct experimentation and by the calculating devices is extremely important.

The writer is interested in this paper from two aspects. First, he has developed at Columbia University a very complete electrical computing machine for heat flow known as the heat- and mass-flow analyser. Comparing our analyser with the computing machine described in the paper, the main differences are that we are using condensers of extremely high leakage resistance of the order of magnitude of 40,000–60,000 megohm $\times$ microfarad. This in connection with the very careful design of the circuits results in a total leakage of 1,000 megohms or more even if we use the total capacity of 2,500 microfarads. This figure of 1,000 megohms compares with the value of 500 megohms given in the paper for a circuit of only 7 microfarads.

The large amount of capacity in combination with the high total resistance enables us to carry out experiments over very much longer times than those mentioned in the paper. The average time of our experiments ranges between 5 and 15 min., as compared with 2 or 3 min. mentioned in the paper. This longer time enables us to change the capacitance and resistance during the experiment either manually or mechanically, thus simulating the change of thermal conductivity and specific heat.

The second point in which the writer is particularly interested is the subject of the examples which the authors describe. We have studied the freezing of metals and are now carrying out experiments on the solidification of castings in which we hope to duplicate direct experiments. In our tests we will start from the liquid stage, taking such values for thermal properties as are available. We are also aware that in a long-range programme it may be possible to determine some properties of liquid metals by the electrical analogy method by trial and error. The first step in such a procedure would be the exact determination of thermal properties below the freezing point. The next step would consist in making actual measurements of freezing times and temperature-time curves in the solid state, starting from molten material. The third step would consist in repeated attempts to duplicate these curves by systematically changing

the circuit during the " liquid period " until the temperatures during the " solid period " checked with those determined by direct experiments. This method is not accurate, but may, if carried out carefully, yield approximate physical constants which would be used in later analyses of size and shape of ingots by means of the analyser.

The statement that it is sufficient to consider the end of the heating-up curve in reheating billets or bars is interesting, but it is based on necessary preliminary experiments to find out the surface-temperature/time curve before utilising the method. Assuming constant physical properties, which, as the examples show, may not be perfectly legitimate, one can calculate readily the constant furnace temperature required to obtain any desired degree of temperature uniformity in the bar or billet. The method for this calculation has been described previously and will be published with complete curves shortly. In view of the fact that properties are not constant it will be necessary to apply in the calculations for stock of different sizes different physical properties, even if the stock is of the same material. As long as determinations of such " apparent properties " have not been carried out the lengthy method of first determining by experiments the surface-temperature/time curve and then calculating the soaking time will be unavoidable. For this purpose a slide rule and alignment chart as developed in the paper will be most helpful.

AUTHORS' REPLY.

The AUTHORS wrote in reply : We are grateful to Dr. Paschkis for his contribution to the discussion. His information regarding his own equipment is particularly valuable, as it indicates that the experimental difficulties met with in the use of the computor can be fully overcome by the use of special electrical equipment which is not at present available to us.

In the computor described in the paper the conductivity and specific heat are not dealt with as such, but are incorporated in the thermal diffusivity, which is varied by adjustment of the time base. For most problems this is mechanically much simpler than the alteration of condensers or resistances during a run.

His suggestion of making use of machine analysis to determine the thermal properties of a material from the observation of the temperature variation has already been tried in a number of cases and has proved a valuable new tool of investigation.

The calculation of temperature changes at a transformation point has been discussed in the second paper referred to ; work on these calculations and also on the liquid–solid transformation has so far been held up by lack of experimental data on the mechanism of transformation.

With regard to the suggestion for determining the constant furnace temperature required to obtain any desired degree of temperature uniformity in the bar or billet, we shall be interested to see the complete curves which Dr. Paschkis proposes to publish, as this represents a feature of the problem which was not dealt with in the paper. We can readily appreciate the value of such information, but in our experience it is a practical problem of considerable difficulty to arrive at a significant experimental value of the effective furnace temperature. It is a considerable idealisation to represent the furnace conditions by a single " furnace temperature," and the problem remains to choose the point of the furnace at which the measured temperature can be taken as a representative " furnace temperature." We considered that with modern methods of pyrometry it was a more simple practical problem to observe the surface temperatures of typical charges.

THE FORMULATION OF ANTI-CORROSIVE COMPOSITIONS FOR SHIPS' BOTTOMS AND UNDERWATER SERVICE ON STEEL.[1]

THE EFFECT OF THE PIGMENT AND OF THE MEDIUM.

By F. FANCUTT, F.R.I.C., A.M.I.Chem.E. (DERBY) AND J. C. HUDSON, D.Sc. (BIRMINGHAM; OFFICIAL INVESTIGATOR TO THE CORROSION COMMITTEE).

(Figs. 1 to 3 = Plates XXV. and XXVI.)

Paper No. 13/1944 *of the Corrosion Committee (submitted by the Marine Corrosion Sub-Committee).*

CONTENTS.

SUMMARY.

This paper is the first of a series in which the results of the Marine Corrosion Sub-Committee's investigations on formulated ships' bottom compositions will be reported. It deals specifically with anti-corrosive compositions; the subject of anti-fouling compositions will be discussed in later contributions relating to other work now in progress.

The results of the Sub-Committee's researches to date on formulated anti-corrosive compositions lead to the following general conclusions :

(i) The *pigment* should be inhibitive in character, but may with advantage be diluted with neutral pigments or extenders, provided that the proportion of inhibitor is not excessively reduced. Basic lead sulphate is a valuable pigment for this type of service, and entered into two of the best formulations in a series in which 77 different pigment combinations were incorporated in the same modified phenolic-resin medium. These two paints were pigmented, respectively, with (a) 8 parts of basic lead sulphate, 2 parts of aluminium and 3 parts of barytes, and (b) 2 parts of white lead, 4 parts of basic lead sulphate and 4 parts of Burntisland red.

(ii) Of the range of *media* so far tested the best have proved to be various types of phenolic- or coumarone-resin varnish and one containing chlorinated rubber.

Further tests are in progress with a view to determining the best combinations of pigment and medium.

INTRODUCTION.

THIS paper presents a brief account of the progress to date of the investigations into the formulation of anti-corrosive compositions for ships' bottoms that the authors are conducting on behalf of the Marine Corrosion Sub-Committee. These have so far involved the preparation in the Paint Laboratory of the London, Midland and Scottish Railway Company's Research Department, Derby, of 267 formulated anti-corrosive paints, together with a number of anti-fouling compositions. The behaviour of the first 140 of these paints, the testing of which is now concluded, will be reported here.

The paints concerned fall into two distinct experimental series designed to test the effect of (A) variations in pigmentation and (B) differences in medium. In series A 77 different pigment formulations were incorporated in the same medium, a modified phenol-formaldehyde-resin/stand-oil varnish.[1] The resulting paints were tested on specimens of steel plate immersed from the Marine Corrosion Sub-Committee's raft at Caernarvon. In series B only three different pigment combinations were used, but each was made up in 21 different media. These 63 paints were tested, also on steel plates, at the Admiralty Corrosion Committee's testing station, Emsworth, Hants., by courtesy of the Admiralty Corrosion Committee.

[1] As will be described later, 8 other formulated paints, prepared by Bakelite, Ltd., were also included in the Caernarvon tests.

In both series of tests, two coats of the formulated anti-corrosive paints were applied beneath a finishing coat of formulated anti-fouling composition, which was the same throughout any one series.

A.—THE EFFECT OF THE PIGMENT.

(1) *Experimental.*

(a) *Preparation of the Paints.*—The 77 paints made at Derby were all formulated in the same modified phenol-formaldehyde-resin/stand-oil varnish, which had the following composition :

Modified phenol-formaldehyde resin [1] . . .	$20 \cdot 0\%$
Stand oil	$40 \cdot 0\%$
White spirit	$39 \cdot 3\%$
Lead-manganese-cobalt driers . . .	$0 \cdot 7\%$

Full details of the method of manufacturing the medium are given in Appendix F (*see* medium No. 2).

TABLE I.—*List of Pigments Tested.*

Pigment.		Number of Paints in Which Included.			
Ref. Letter.	Name.	Single Pigment.	Binary Mixtures.	Ternary Mixtures.	Total.
a	Red lead	1	9	13	23
b	White lead	1	8	8	17
c	Basic lead sulphate	1	7	11	19
d	Burntisland red	1	9	12	22
e	Barytes	...	1	11	12
f	Graphite	1	8	5	14
g	Aluminium	1	4	5	10
h	Red oxide	1	4	3	8
j	Zinc oxide	...	9	3	12
k	Bideford black	...	4	4	8
m	Zinc dust	...	4	4	8
n	Barium chromate	...	3	3	6
p	Witherite	...	1	4	5
q	Zinc chromate	...	4	1	5
r	Zinc tetrahydroxy-chromate	...	3	...	3
s	Chromated zinc oxide	...	2	...	2
t	Lithopone	1	...	...	1
	Number of paints	8	40	29	77

The pigments incorporated in this medium are listed in Table I. They were used either alone or in various binary or ternary combinations, as shown in Table II.[2] The whole of each pigment

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[1] The particular resin used was Bedesol 66 (Imperial Chemical Industries, Ltd.).

[2] The system of designating the paints is as follows : acp 283 denotes a paint in which the pigment consists of a mixture of pigments a, c and p (*i.e.*, red lead, basic lead sulphate and witherite, respectively) in the proportion by weight of $2 : 8 : 3$.

TABLE II.—*Details of Pigment Mixtures.*[1]

Pigment.		Mixtures Tested.							
Ref. Let-ter.	Name.	Com-position.	Paint No.	Com-position.	Paint No.	Com-position.	Paint No.	Com-position.	Paint No.
a	Red lead	*a* 10	1	*abp* 643	11	*ad* 28	7	*afk* 282	69
		ab 64	2	*ac* 28	10	*adg* 181	22	*ah* 28	6
		ab 37	3	*acd* 244	21	*adk* 244	19	*ahp* 283	12
		abc 238	18	*ace* 283	15	*adp* 283	13	*ak* 28	5
		abd 238	17	*ack* 244	20	*ae* 73	9	*ap* 73	8
		abf 238	16	*acp* 283	14	*af* 28	4	...	...
b	White lead	*b* 10	23	*bcf* 244	31	*bdf* 244	30	*bj* 82	33
		bc 28	28	*bd* 28	27	*bf* 28	24	*bk* 28	25
		bcd 244	32	*bde* 283	29	*bh* 28	26	...	...
c	Basic lead sul-phate	*c* 10	66	*cem* 832	65	*cj* 82	46	*cq* 82	41
		ceg 832	58	*cen* 832	38	*cm* 82	62	...	...
		cej 832	47	*cg* 82	55	*cn* 82	36	...	...
d	Burntisland red	*d* 10	71	*den* 832	37	*dj* 73	51	*dq* 82	40
		deg 832	57	*dg* 82	54	*dm* 82	61	*dr* 82	75
		dem 832	64	*dgj* 415	48	*dn* 82	35	*ds* 82	43
e	Barytes	*egh* 328	56	*ehm* 382	63	...	...	...	...
f	Graphite	*f* 10	67	*fkn* 822	70	*fr* 82	74	...	...
		fj 82	44	*fn* 82	34	*fs* 82	42	...	...
		fk 82	68	*fq* 82	39	...	...	...	...
g	Aluminium	*g* 10	52	*gh* 28	53	*gj* 82	59	...	...
h	Red oxide	*h* 10	72	*hm* 82	60	...	...	...	...
j	Zinc oxide	*jk* 28	45	*jmq* 721	49	*jr* 13	84	...	...
		jm 82	50	*jq* 3/11	85	...	...	...	...
t	Lithopone	*t* 10	73	...	...	...	...	...	...

[1] To avoid unnecessary duplication the pigments have been arranged in alphabetical order of reference letters. Hence, in all cases other than *a* (red lead), mixtures containing a given pigment may also be found under earlier letters of the alphabet.

concerned was taken from the same batch, which was analysed, as detailed in Appendix A. The pigments were ground with the necessary quantity of medium to give workable pastes. The paints were prepared in half-gallon lots by milling these pastes in the requisite proportions with the remainder of the medium. Thinners were added as required to reduce the mixed paints to a suitable consistency, which was checked by a brushing-out test on a steel panel. The mixed paints were allowed to stand for one week, after which another brushing test was made and the consistency finally adjusted, if necessary, by the addition of further quantities of thinners. The viscosity and specific gravity of each paint were then determined.

Eight additional paints were prepared for test by Bakelite, Ltd. These represented combinations of pigment mixtures suggested by the authors with water- and alkali-resistant varnishes based on 100% phenolic resins suggested by this firm. Particulars of the three media concerned and the approximate pigmentations used in

each case are given in Table III.; fuller details of these paints will be found in Appendix B.

TABLE III.—*Formulations of the* 100% *Phenolic-Resin Varnishes.*

	Varnish *P*.		Varnish *Q*.		Varnish *R*.	
Bakelite Resin No.	*R*254 . . 20%		*R*10840 . . 12·1%		*R*254 . . 22·6%	
Oils	Linseed oil . 20% Tung oil . . 20%		Tung oil . . 47·1%		Linseed oil . 45·2%	
Thinners	White spirit, &c.. 40%		White spirit . 39·2%		White spirit . 31·7%	
Driers	...		Pb–Co naphthe- nates . . 1·7%		Pb–Co–Mn naphthenates 0·5%	
		Paint No.		Paint No.		Paint No.
Pigment formu- lations	*ab* 32	77	*ab* 32	81	*ab* 32	83 [1]
	d 10	80	...	...	...	...
	jgd 514	79	*jgd* 514	82	...	...
	qd 14	78	...	...	...	...
	qu 41	76	...	...	...	...

[1] Paint No. 80, *d* 10/*P*, was used as a second coat over a priming coat of this paint.

The keeping properties of the paints were investigated by subjecting pint tins of each to storage tests at Derby (ordinary room temperature) and in a climatic hut at Woolwich (constant temperature of 120° F.), respectively, in the latter case through the kind arrangement of the Chief Superintendent, Armaments Research, for a period of 6 months or more, after which the condition of the paints in the tin was observed and their working properties were redetermined.

As already stated, in the immersion tests at Caernarvon two coats of each paint were applied to steel specimens. A single coat of the same anti-fouling composition, reference *AF*8/42, was applied over each. The formulation of this composition is summarised in Table IV.

(b) *Preparation of the Specimens.*—The steel specimens used for testing the paints were 15 in. long by 10 in. wide and had been cut from $\frac{1}{4}$-in. ships' plate of acid open-hearth steel with the following average analysis :

Carbon.	Manganese.	Silicon.	Phosphorus.	Sulphur.	Copper.
0·17%	0·53%	0·02–0·03%	0·05%	0·05%	0·15%

Each paint was tested on two specimens in differing surface conditions as follows :

(i) As-rolled specimens exposed to weathering at Birmingham for 3 months (May 15 to August 22, 1942). These specimens suffered an average loss on weathering and wirebrushing of

11 g.[1]; on the average they had shed 92% of their mill scale.[2]

TABLE IV.—*Compositions of the Formulated Anti-Fouling Paints.*

Reference :	AF8/42.		AF1/43.	
Toxins	Cuprous oxide	15·6%	Cuprous oxide	16·2%
	Mercuric oxide	7·8%	Mercuric oxide	8·1%
Secondary pigments	Red oxide (Indian red)	20·4%	Burntisland red	23·9%
			Asbestine	14·6%
			Calcium sulphate	2·9%
Non-volatile medium	Heavy litho varnish	11·3%	Heavy litho varnish	4·5%
	Congo ester	3·8%	Congo ester	1·5%
	Rosin	9·0%	Rosin	9·1%
			Green oil	2·5%
Thinners	Naphtha	23·9%	Naphtha	12·3%
	Dipentene	6·7%	Dipentene	4·4%
Drier		1·5%		...
Weight per gal.	15·0 lb.		19·8 lb.	
Efflux time [1]	47 sec.		93 sec.	
Method of manufacture.	Fuse rosin and toxins together for 1 hr. at 180° C. While still hot add the litho-varnish / Congo-ester (for preparation *see* Appendix F, medium No. 20). Thin, mix in red oxide and grind in cone mill.		Dissolve rosin in thinner, add litho-varnish / Congo-ester (for preparation *see* Appendix F, medium No. 20) and green oil. Mix in toxins and secondary pigments. Grind in cone mill.	

[1] First 50 c.c. from a full No. 4 Ford cup at 70° F.

(ii) Specimens descaled by pickling in cold 5% by volume hydrochloric acid, and subsequently exposed to the weather at Birmingham for 6 days (August 22–28, 1942).[3] The effect of the weathering treatment was to cover the surface of the specimens with a light film of rust, which was largely removed by the wire-brushing before painting. The gain in weight of

[1] For convenience, changes in weight are given here and elsewhere in the units in which they were measured, *viz.*, grammes per specimen. To convert into ounces per square foot these values should be multiplied by 0·016. The weight of mill scale on a specimen would be of the order of 50 g., or 0·8 oz. per sq. ft. The apparent discrepancy between the average loss in weight on weathering, 11 g., and that which would correspond to the amount of mill scale shed, *i.e.*, 92% of 50 g., or 46 g., is due to the counter-acting effect of the increase in weight resulting from the accumulation of rust on the specimens.

[2] More precisely the observations for the family of 94 specimens from which the specimens concerned were taken at random were :

Loss in weight, g. per specimen : Average 10·9; standard deviation 6·2. Descaling, % : Average 91·9; standard deviation 11·0.

[3] The choice of this short weathering period was not deliberate. It was decided to weather the specimens at a late stage in the proceedings ; the original plan was to paint over the freshly pickled surface.

the specimens on weathering varied from nil to 2 g.; this difference has little significance.

(c) *Painting of the Specimens.*—The specimens were painted by hand in a boat shed at Caernarvon between September 4 and 20, 1942; 2-in. flat bristle brushes were used, with $\frac{1}{2}$-in. round brushes for the edges and identification marks. The first coat of all the anti-corrosive paints was applied between September 4 and 8. Thereafter the painting and exposure of the specimens were completed in batches of 40 or 48, an interval of 24 hr. being allowed between the second anti-corrosive and the anti-fouling coats. The latter was always applied in the morning, so that the specimens could be immersed during the same afternoon after an interval of not less than 4 hr.

The whole of the painting was done by the same two research assistants, each of whom painted both specimens coated with the same paint in the case of any one coat, but, to minimise any personal factor, the sets of specimens were interchanged for successive coats.

The weight of wet paint used was determined by weighing the paint container and brushes before and after coating each specimen. This was done for all three coats. The weight of dry paint was also determined by weighing each specimen before painting and after each coat had dried. This was done only for the two anti-corrosive coats, as it was not practicable to weigh the specimens after the anti-fouling compositions had dried. Temperature and humidity records were taken while the painting was in progress. Further details concerning the painting of the specimens will be found in Appendix D; a summary of the observations is given in Table V.

TABLE V.—*Painting of the Specimens.   Series* A.   *Caernarvon.*

	Number of Observations.		Max.		Min.		Mean.		Standard Deviation.		90% Range.[2]	
Atmospheric temp. °F.	72		63		54		59		...		...	
Relative humidity. %	72		97		77		89		...		...	
	I.	II.	I.	II.	I.	II.	I.	II.	I.	II.	I.	II.
Spreading rate of paints. Sq. yd. per gal.[1] : 1st coat. $AC1$.	85	85	109	140	56	61	78	96	12	18	97– 58	126– 66
2nd coat. $AC2$.	85	85	172	192	58	62	100	112	25	31	141– 59	162– 62
3rd coat. $AF3$.	85	85	121	142	60	64	89	94	14	16	112– 66	120– 68

[1] I.—On as-rolled specimens weathered for 3 months.   II.—On pickled specimens weathered for 6 days.
[2] Approximate limiting values containing 90% of the observations calculated as the mean value $\pm$ 1·645 times the standard deviation.

During the painting itself it was noted that a reaction took place between anti-corrosive compositions containing aluminium pigment and the anti-fouling composition. This was traced ultimately to the formation of alumina due to interaction between the metallic pigment contained in the anti-corrosive paint and the mercury compound present in the anti-fouling composition. For this reason, paint No. 72A, pigmented with red iron oxide,[1] was substituted for the second coat of all paints containing aluminium or metallic zinc, where second coats had not already been applied.

(d) *Immersion of the Specimens at Caernarvon.*—The conditions of immersion at Caernarvon have already been described.[2] The specimens were exposed on the larger raft, which, it may be recalled, is moored in the Menai Straits, about $\frac{1}{2}$ mile out from the harbour; the tide varies from about $1\frac{1}{2}$ to 5 knots. Two types of exposure frame were used, single frames carrying four specimens in one row, and double frames carrying two rows of four specimens each, one above the other. The depth of immersion to the top edge of the specimens in the upper row was 18–24 in.; in the case of the double frames, the specimens in the lower row were 18 in. below this. The specimens were secured to the frames by two $\frac{3}{8}$-in. steel bolts passing through suitable insulating sleeves. The nuts and bolt heads were coated with anti-fouling composition, as were also the exposure frames, which had been previously painted with anti-corrosive compositions.

In order to minimise any positional effect on the raft [3] care was taken that duplicate specimens should be exposed in opposite halves of the raft and in the upper and lower rows of the frames concerned, respectively. Otherwise, apart from restrictions imposed by the necessity of dealing with the specimens in multiples of 8, the allocation was at random.

(e) *Inspections during Exposure.*—The specimens were inspected *in situ* on six occasions between their immersion in September, 1942, and their removal from test in May, 1943, after 36 weeks' exposure. On these occasions records of the fouling of the specimens and of the condition of the paint film were taken in a standard manner, as already described.[4]

(f) *Final Examination in the Laboratory.*—Gross fouling was removed at the testing station before returning the specimens to the laboratory for the final examination. This examination was conducted as follows :

(i) The specimens were cleaned by bristle brushes under running water, allowed to dry and reweighed, so as to determine the loss in weight on exposure.

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[1] See Footnote 2 to Table VII.

[2] First Report of the Marine Corrosion Sub-Committee, *Journal of The Iron and Steel Institute*, 1943, No. I., p. 355 P.

[3] Statistical analysis of the results has since shown that any such positional effect is not pronounced.

[4] First Report of the Marine Corrosion Sub-Committee, *loc. cit.*, p. 356 P.

(ii) Their surface was examined in detail by superposing a grid masking the edges and leaving an area of 100 sq. in. exposed in the middle. This was subdivided into six areas, each of approximately 16 sq. in. For each of these areas, the following quantities were estimated :

A.—Whole paint film intact, % by area.

B.—Anti-corrosive paint only intact, *i.e.*, anti-fouling flaked off, % by area,

C.—Bare metal, *i.e.*, areas from which all the paint film had been removed but where the metal had not rusted, % by area.

D.—Rust, *i.e.*, areas devoid of paint and where the metal had rusted, % by area.

E.—Depth of pitting, if any, mils.[1]

In cases *A* to *D*, the mean values for all six sub-areas were calculated for each side separately.

(2) *Results*.

(a) *Visual Inspection—Fouling*.—The performance of the anti-fouling paint *AF*8/42 proved disappointing, since hydroid fouling developed rapidly on all the specimens and they were found to be heavily fouled at the first inspection after 6 weeks. Fortunately, owing to the winter season, this remained the only major type of fouling, and it was possible to inspect the coatings until April, 1943, when young barnacles settled on the surfaces. These grew rapidly, and the specimens were removed in May, 1943, after 36 weeks' immersion, since further detailed inspection beneath the heavy growth of shell had become impossible ; on this last occasion the fouling was detached before making the observations on the condition of the paint film.

(b) *Relative Behaviour of the Anti-Corrosive Compositions*.—A full statement of the experimental results is made in Appendix E. It is unnecessary to detail these here, but it is desirable to state the method adopted in making the assessments. These are based on the joint consideration of the following observations :

(i) The index figure deduced from the visual inspections throughout exposure.[2]

[1] The pits were also classified thus as regards diameter : *f*, fine, less than 2 mm. dia.; *m*, medium, 2–10 mm. dia.; *c*, coarse, more than 10 mm. dia.

[2] The index figure is arbitrarily taken as the sum for both faces of the specimen of the percentage of blistering plus twice the percentage of flaking plus four times the percentage of rusting; in this particular series of tests a cumulative figure has been used—*i.e.*, the calculated values at all inspections have been added together.

(ii) The loss in weight on exposure of the specimens painted over the pickled surface.[1]

(iii) The extent of rusting found on the specimens on examination in the laboratory.

(iv) The amount of intact paint left on the specimens at the final examination.

Except in case (ii), separate estimates were made for each specimen of a pair. There are thus seven distinct criteria of performance and the 85 paints have been classified in respect of each of these as " very good," " good," " moderate " or " bad." By assigning numerical values of 3, 2, 1 and 0, respectively, to these four classes, a merit figure for each paint is obtained by addition, the maximum possible value of which is 21 for a paint classified as very good throughout.

The limits between the moderate and bad classes were chosen as follows :

(a) In the case of the index figure and the percentage of rusting, the limit corresponds to 10% of rust or its equivalent on each face.

(b) In the case of loss in weight and the amount of intact paint, the average value for all the 85 paints was taken.

In all cases the very-good/good boundary has been fixed at two-tenths and the good/moderate boundary at five-tenths of the range between " perfection " and the moderate/bad boundary. This will be evident from the statement shown in Table VI.

TABLE VI.—*Classification Limits. Series* A. *Caernarvon.*

Class.	Score.	Index Figure.	Rusting. Parts per 200.[1]	Intact Paint. Parts per 200.[1]		Loss in Weight. G. per Specimen.
				I.	II.	
V Very good.	3	0–56	0–3	200–197	200–191	0–5
G Good	2	57–143	4–9	196–193	190–177	6–13
M Moderate .	1	144–286	10–19	192–185	176–154	14–27
B Bad .	0	287 and over	20 and over	184 and less	153 and less	28 and over

[1] Sum of the observations (%) on the front and back surfaces. I.—As-rolled and weathered specimen. II.—Pickled and weathered specimen.

Results obtained in this manner for the 85 paints are given in Table VII.

[1] As discussed in Appendix E, differences in the weight changes in the case of specimens painted over the weathered rolling scale are not significant.

TABLE VII.—*Results of Caernarvon Tests on Effect of Different Pigments in Anti-Corrosive Compositions.*

| Paint. | | Gradings.[1] | | | | | | | | Storage Properties.[1] |
| No. | Formulation. | Index Figure. | | Rusting. | | Intact Paint. | | Loss in Weight. II. | Total (Merit Figure). | |
		I.	II.	I.	II.	I.	II.			
1	*a* 10	1	2	0	1	0	0	0	4	*B*
2	*ab* 64	1	2	1	3	0	3	2	12	*B*
3	*ab* 37	1	2	2	2	2	2	1	12	*B*
4	*af* 28	0	0	0	0	0	1	1	2	*G*
5	*ak* 28	3	1	3	2	3	2	2	16	*G*
6	*ah* 28	1	1	1	0	1	0	0	4	*M*
7	*ad* 28	1	1	2	3	2	3	1	13	*B*
8	*ap* 73	3	1	3	2	2	0	0	11	*B*
9	*ae* 73	3	1	2	2	2	0	0	10	*B*
10	*ac* 28	0	3	2	3	1	2	2	13	*B*
11	*abp* 643	3	1	3	1	3	0	0	11	*B*
12	*ahp* 283	0	2	3	2	2	0	0	9	*B*
13	*adp* 283	0	0	2	3	1	3	0	9	*B*
14	*acp* 283	1	3	3	3	2	2	3	17	*B*
15	*ace* 283	2	3	2	3	2	3	2	17	*B*
16	*abf* 238	0	0	1	1	1	2	2	7	*G*
17	*abd* 238	2	2	3	3	3	3	1	17	*B*
18	*abc* 238	2	3	3	3	2	3	2	18	*B*
19	*adk* 244	3	0	0	0	0	0	0	3	*G*
20	*ack* 244	2	2	1	2	0	2	2	11	*G*
21	*acd* 244	3	3	3	3	3	3	2	20	*M*
22	*adg* 181	1	0	1	2	0	3	1	8	*B*
23	*b* 10	1	1	2	2	1	2	1	10	*B*
24	*bf* 28	1	0	0	1	0	2	1	5	*V*
25	*bk* 28	1	0	1	2	1	3	1	9	*G*
26	*bh* 28	1	1	1	1	0	1	0	5	*G*
27	*bd* 28	1	1	0	2	0	3	1	8	*M*
28	*bc* 28	2	3	2	2	1	2	2	14	*B*
29	*bde* 283	3	0	1	2	1	3	0	10	*M*
30	*bdf* 244	0	0	2	1	2	2	1	8	*G*
31	*bcf* 244	0	0	1	0	0	1	1	3	*G*
32	*bcd* 244	3	3	3	2	2	3	1	17	*G*
33	*bj* 82	1	1	2	1	2	0	0	7	*G*
34	*fn* 82	0	0	1	0	0	1	2	4	*G*
35	*dn* 82	0		1	2	0	2	0	5	*B*
36	*cn* 82	1	3	2	1	2	0	1	10	*M*
37	*den* 832	1	1	1	1	1	2	0	7	*B*
38	*cen* 832	3	3	2	2	1	2	2	15	*M*
39	*fq* 82	0	0	1	0	0	2	2	5	*G*
40	*dq* 82	3	0	3	0	3	0	0	9	*B*
41	*cq* 82	3	3	2	2	2	2	1	15	*M*
42	*fs* 82	0	0	0	1	0	1	1	3	*V*
43	*ds* 82	2	1	1	2	1	3	1	11	*B*
44	*fj* 82	0	1	0	1	0	0	0	2	*G*
45	*jk* 28	2	0	1	0	0	0	0	3	*G*
46	*cj* 82	1	3	2	2	0	1	1	10	*B*
47	*cej* 832	2	2	2	1	1	1	2	11	*B*
48	*dgj* 415	3	1	2	1	2	0	0	9	*M*
49	*jmq* 721	0	0	0	0	0	0	0	0	*G*
50	*jm* 82	1	0	1	0	0	0	0	2	*G*
51	*dj* 73	2	0	3	1	3	1	0	10	*M*
52	*g* 10 [2]	2	1	1	1	1	2	1	9	*G*
53	*gh* 28 [2]	1	1	0	1	0	2	0	5	*M*
54	*dg* 82 [2]	2	0	2	0	2	0	0	6	*M*
55	*cg* 82 [2]	2	3	2	2	2	3	3	17	*G*

TABLE VII.—(*Continued.*)

Paint.		Gradings.[1]								Storage Pro-perties.[1]
No.	Formulation.	Index Figure.		Rusting.		Intact Paint.		Loss in Weight. II.	Total (Merit Figure).	
		I.	II.	I.	II.	I.	II.			
56	egh 328	1	0	0	0	0	0	0	1	M
57	deg 832	1	0	2	0	1	0	0	4	G
58	ceg 832 [2]	3	3	3	2	3	3	3	20	G
59	gj 82	2	1	3	2	2	1	2	13	G
60	hm 82	0	0	1	0	0	0	0	1	M
61	dm 82	1	1	2	2	1	2	0	9	B
62	cm 82 [2]	1	3	2	3	1	3	2	15	B
63	ehm 382 [3]	3	0	2	0	2	0	0	7	M
64	dem 832	3	1	3	2	3	3	0	15	M
65	cem 832	2	3	2	3	1	3	3	17	B
66	c 10	1	2	2	1	1	1	2	10	B
67	f 10	0	0	0	0	0	0	1	1	G
68	fk 82	1	0	1	0	0	1	2	5	G
69	afk 282	1	0	0	0	0	1	2	4	G
70	fkn 822	1	0	2	0	2	1	2	8	G
71	d 10	0	0	1	2	1	2	0	6	M
72	h 10	2	0	0	0	0	0	0	2	M
73	t 10	2	0	1	0	0	0	0	3	B
74	fr 82	0	0	0	1	0	0	0	1	G
75	dr 82	2	2	0	3	0	0	0	7	B
84	jr 13 [3]	2	1	3	2	2	0	1	11	G
85	jq 3/11	3	3	3	2	3	3	3	20	G
Paints in 100% Phenolic-Resin Media.										
76	qu 41/P	1	2	2	2	0	3	1	11	M
77	ab 32/P	3	3	2	3	2	3	2	18	M
78	qd 14/P	2	1	2	3	2	3	1	14	M
79	jgd 514/P	1	0	2	0	1	0	1	5	V
80	d 10/P	2	1	2	1	1	0	1	8	G
81	ab 32/Q	2	3	2	2	2	1	2	14	M
82	jgd 514/Q	1	2	1	1	0	0	0	5	V
83	ab 32/R; d/P	2	3	2	3	0	1	1	12	M

[1] $3 = V$ = very good; $2 = G$ = good; $1 = M$ = moderate; $0 = B$ = bad. I. = as-rolled and weathered specimen; II. = pickled and weathered specimen.

[2] Paint No. 72 was used as the second anti-corrosive coat in the case of these painting systems; it was first thinned with 10% by weight of the varnish medium, and was then known as paint No. 72A.

[3] The pickled specimens used for the tests on paints Nos. 84 and 85 had been exposed to the weather for $2\frac{1}{2}$ months instead of 6 days. Moreover, in the case of paint No. 85 only, both specimens were treated with a panel wash before being painted. (The reason for these differences was that the specimens concerned were originally intended for tests on other materials which failed to arrive, so these two additional formulated paints were included in the programme at the last minute.) The panel wash consisted of a solution of phosphoric acid (sp. gr. 1·70) 35%, in methylated spirit 61 O.P. 65% by weight. It was applied with a clean brush, allowed to dry for $\frac{1}{2}$ hr. and washed off with clean fresh water, and the paints were applied after the specimens had dried again. (*N.B.*— When using this panel wash the final drying after washing off with water should be conducted quickly, the use of hot water or slight artificial heat being advantageous.)

(3) *Discussion of Results.*

(a) *The Best Anti-Corrosive Compositions.*—As is explained in Appendix E, no one method of assessing paint performance is infallible, but it is obvious that any paint with a high merit figure is a good one. None of the 85 paints has the maximum possible merit figure of 21, but there are 11 paints with values of 17 or more.

These are listed in Table VIII. It will be observed that they all contain high proportions of inhibitive (rust-preventing) pigments,

TABLE VIII.—*Short List of the Best Paints in the Caernarvon Tests.*

Merit Figure.	Paint.			Storage Properties.
	No.	Reference.	Pigmentation. Parts by Weight.	
20	21	acd 244	Red lead 2, basic lead sulphate 4, Burntisland red 4.	Moderate.
	58	ceg 832 [1]	Basic lead sulphate 8, aluminium 2, barytes 3.	Good.
	85	jq 3/11 [2]	Zinc oxide 3, zinc chromate 11.	Good.
18	18	abc 238	Red lead 2, white lead 3, basic lead sulphate 8.	Bad.
	77	ab 32/P	Red lead 3, white lead 2 (in 100% phenolic-resin varnish P).	Moderate.
17	14	acp 283	Red lead 2, basic lead sulphate 8, witherite 3.	Bad.
	15	ace 283	Red lead 2, basic lead sulphate 8, barytes 3.	Bad.
	17	abd 238	Red lead 2, white lead 3, Burntisland red 8.	Bad.
	32	bcd 244	White lead 2, basic lead sulphate 4, Burntisland red 4.	Good.
	55	cg 82 [1]	Basic lead sulphate 8, aluminium 2.	Good.
	65	cem 832	Basic lead sulphate 8, zinc dust 2, barytes 3.	Bad.

[1] *See* footnote 2 to Table VII.
[2] *See* footnote 3 to Table VII.

such as red lead, white lead, basic lead sulphate or zinc chromate. The first conclusion to be drawn from the results, therefore, is that for the pigmentation of anti-corrosive paints for use on steel immersed in sea water inhibitive pigments of these or other types are to be preferred to neutral pigments such as red oxide.

Since ships' compositions have to be exported for use to the four corners of the earth, stability in storage is an essential property and must be taken into account in the evaluation of any ships' compositions. The results of the storage tests described in Appendix C are summarised for the 11 best paints in Table VIII., and emphasise the need for further study of these properties. If the authors had to choose an anti-corrosive composition for large-scale application on the basis of the results of this series of tests, their choice would be paint No. 32 (details of which are given in Table IX.). In deciding between the paints detailed in Table VIII., the authors have been influenced by the fact that all but four require further study in regard to storage properties, whilst of the remaining four, namely,

TABLE IX.—*Formulation and Properties of Paint No. 32.*

Formulation.		Properties.
	% by Weight.	
White lead	13·6	Weight. Lb. per gal. . 21·6
Basic lead sulphate .	27·2	Efflux time. Sec.[1] :
Burntisland red	27·3	Original . . . 41
Modified phenolic-resin/		(D) After 9 months at
stand-oil varnish	23·5	room temp. . . 39
Naphtha	7·2	(W) After 6 months at
Dipentene	1·2	120° F. and 3 months
		at room temp. . . 208
		Remixing (r) and application (a)
		after storage :
		(D)—(r) easy; (a) satisfactory.
		(W)—(r) rather difficult; (a)
		pulls.

[1] Efflux time for first 50 c.c. from a full No. 4 Ford cup at 70° F.

No. 58 (basic lead sulphate 8, aluminium 2, barytes 3 parts), No. 85 (zinc oxide 3, zinc chromate 11 parts), No. 32 (white lead 2, basic lead sulphate 4, Burntisland red 4 parts) and No. 55 (basic lead sulphate 8, aluminium 2 parts), No. 55 can be dismissed as being slightly inferior to No. 58, which has substantially the same formulation.   The behaviour of No. 85 may have been enhanced by the fact that the specimens to which it was applied were treated with an inhibitive wash [1]; in any case, its pigment is a binary mixture containing a high percentage of zinc chromate, so that the authors prefer to regard it as the prototype of a family of paints based on the ternary pigment system zinc-oxide/zinc-chromate/extender earmarked for further study rather than as a paint to be put into service at once.   The presence of aluminium in No. 58 militates against its use under present circumstances, since this material is in short supply.

(b) *Effect of Individual Pigments.*—The behaviour of a given pigment cannot be dissociated from the properties of any other pigments with which it may be admixed nor from those of the medium in which it is bound.   Consequently, it would be unwise to enter into a detailed discussion of the relative merits of the different pigments for use in underwater anti-corrosive compositions, but the following broad conclusions seem to be warranted :

(i) Basic lead sulphate is a particularly valuable pigment, since, of the 15 formulations in which it occurs as the major constituent, none has failed to give better than average performance.   In this medium it behaved better than red or white lead, between which two pigments there was little to choose, save that the storage properties of formulations with white

[1] *See* Table VII., footnote 3.

lead were rather better than those of equivalent formulations with red lead.

(ii) Red lead used alone did not behave well, owing to a development of brittleness in the paint film. This tendency was reduced when the red lead was blended with white lead, basic lead sulphate or extenders.

(iii) Burntisland red is to be preferred to the red oxide tested [1] (compare paints Nos. 71 and 72, Nos. 7 and 6, &c.). In fact, the latter pigment appeared unsatisfactory, and in several cases the poor paint performance was associated with a high content of this pigment. It may be remarked that, since the term " red oxide " is used in the trade to cover a wide variety of pigments, material of this type should always be purchased to a specification.

(iv) The type of graphite used in this series of paints proved unsuitable for use as a major constituent in under-water compositions, and for this reason Bideford black has given rather better results (compare paints Nos. 4 and 5). This does not necessarily preclude the use of graphite of other qualities or in other proportions in specially adapted media.

(v) In this particular medium the use of zinc dust as an inhibitive pigment generally proved unsatisfactory.[2] Several tins of the paint incorporating this pigment became blown on storage at 120° F. for less than the full period of 6 months.

Conclusions (i), (iii) and (iv) are illustrated by the data given in Table X., where the average merit figure has been calculated for individual pigments entering into the formulation of at least three paints to an extent of 50% or more of the pigment content.[3] It may

TABLE X.—*Average Merit Figures for Various Pigments.*

In a modified phenolic-resin/stand-oil varnish.

Pigment.				Number of Paints.	Average Merit Figure.
c Basic lead sulphate	.	.	.	15	14·6
b White lead	.	.	.	3	9·7
k Bideford black .	.	.	.	3	9·3
a Red lead .	.	.	.	4	9·3
d Burntisland red	.	.	.	17	·9·1
h Red oxide	.	.	.	8	4·3
f Graphite .	.	.	.	12	3·9
j Zinc oxide	.	.	.	3	3·7

[1] For the analyses of the actual pigments used, *see* Appendix A.

[2] Paints Nos. 62 and 65, with merit figures of 15 and 17, respectively, are interesting exceptions to this statement.

[3] For instance, white lead (b) predominates in paints Nos. 3 (ab 37), 23 (b 10) and 33 (bj 82), with merit figures of 12, 10 and 7, respectively. The mean value of these, 9·7, is given in Table X.

be noted that two of the three paints in which zinc oxide was the major constituent also contained zinc dust, so that the low merit figure for zinc oxide shown in Table X. may not be representative.

(c) *General Comments.*—The following general comments may be made :

(i) A detailed study of the merit figures makes it evident that, in general, better results have been obtained from ternary pigment mixtures than from binary mixtures or from the single pigments themselves. This point is illustrated by the data given in Table XI. for twelve different pairs of paints which differ only in that the

TABLE XI.—*Effect of Additions of Barytes on Paint Performance.*

No Barytes.			Barytes Addition.		
Paint.		Merit Figure.	Paint.		Merit Figure.
No.	Pigment.[1]		No.	Pigment.[1]	
1	*a* 10	4	9	*ae* 73	10
10	*ac* 28	13	15	*ace* 283	17
27	*bd* 28	8	29	*bde* 283	10
35	*nd* 28	5	37	*nde* 283	7
36	*nc* 28	10	38	*nce* 283	15
46	*jc* 28	10	47	*jce* 283	11
53	*gh* 28	5	56	*ghe* 283	1
54	*gd* 28	6	57	*gde* 283	4
55	*gc* 28	17	58	*gce* 283	20
60	*mh* 28	1	63	*mhe* 283	7
61	*md* 28	9	64	*mde* 283	15
62	*mc* 28	15	65	*mce* 283	17
	Mean	8·6		Mean	11·2

[1] For key to pigments *see* Table I.

second member of each pair contains an admixture of barytes. In 10 cases out of 12 the addition of the extender has resulted in improved performance [1]; there was also a slight indication of an improvement in storage qualities (*see* Table VII.).

Consequently, the controlled addition of extender or inert pigments to inhibitive anti-corrosive primers is to be regarded as a legitimate and beneficial step. The validity of this principle has long been recognised in the paint industry, but it will serve a useful purpose to reiterate it and substantiate the assertion with experimental data.

(ii) A second broad principle should be enunciated, however, namely, that there is a limit to the degree to which inhibitive

[1] It is fair to add, with regard to the two exceptions, *i.e.*, paints Nos. 53 (*gh* 28) and 54 (*gd* 28), that in all probability these contained insufficient proportions of inhibitive pigment before the barytes additions (*cf.* the remarks in the next sub-section (*c*) (ii)).

pigments can be diluted with inert pigments or extenders without impairing the protective properties of the paint. As an example of this, if the merit figures for the family of 34 paints pigmented with red lead, white lead or both these pigments are considered, it will be found, as is shown in Table XII., that the average value for

TABLE XII.—*Effect of Admixture of Other Pigments and Extenders to Red and/or White Leads.*

Lead Pigments Predominate.			Other Pigments Predominate.		
Paint.		Merit Figure.	Paint.		Merit Figure.
No.	Pigment.[1]		No.	Pigment.[1]	
1	*a* 10	4	4	*af* 28	2
2	*ab* 64	12	5	*ak* 28	16
3	*ab* 37	12	6	*ah* 28	4
8	*ap* 73	11	7	*ad* 28	13
9	*ae* 73	10	12	*ahp* 283	9
10	*ac* 28	13	13	*adp* 283	9
11	*abp* 643	11	16	*abf* 238	7
14	*acp* 283	17	17	*abd* 238	17
15	*ace* 283	17	19	*adk* 244	3
18	*abc* 238	18	22	*adg* 181	8
20	*ack* 244	11	24	*bf* 28	5
21	*acd* 244	20	25	*bk* 28	9
23	*b* 10	10	26	*bh* 28	5
28	*bc* 28	14	27	*bd* 28	8
31	*bcf* 244	3	29	*bde* 283	10
32	*bcd* 244	17	30	*bdf* 244	8
33	*bj* 82	7	69	*fka* 822	4
	Mean	12·2		Mean	8·1

[1] For key to pigments *see* Table I.

formulations in which the lead pigments [1] predominate is 12·2; this is greater than the average figure, 8·1, for the paints in the opposite category. It should be noted that a number of the latter contain Burntisland red, which has inhibitive properties. If these paints are eliminated from the computation the average figure for this group of paints becomes 6·8.

It is obvious that one object of a research such as this should be to determine the minimum proportion of a given inhibitive pigment needed to give adequate protection from rusting, since apart from the fact that extender additions up to or near to this limit may yield better paints, the cost will presumably be decreased thereby.

(iii) It is interesting to consider the pigmentations of the paints that behaved worst in these tests in the light of the preceding

[1] Including basic lead sulphate, where present.

remarks.   A list of all paints with merit figures of 4 or less will be found in Table XIII.; the authors' views as to the probable cause of failure are also indicated and need no elaboration.

TABLE XIII.—*Short List of the Worst Paints*.[1]

Cause of Failure.[2]	Merit Figure 4.		Merit Figure 3.		Merit Figure 2.		Merit Figure 1.		Merit Figure 0.	
	No.	Formu-lation.	No.	Formu-lation.	No.	Formu-lation.	No.	Formu-lation.	No.	Formu-lation.
Brittleness and flaking of paint film.	1	*a* 10	...	...	...	...	...	...	...	...
Insufficient inhibitive pigment present [3] and/or excessive content of red oxide.	6 57 ...	*ah* 28 *deg* 832 ...	19 45 73	*adk* 244 *jk* 28 *t* 10	72	*h* 10	56 60 ...	*egh* 328 *hm* 82 ...	... ...	... ...
Presence of high proportion of graphite.	34 69	*fn* 82 *afk* 282	31 42	*bcf* 244 *fs* 82	4 44	*af* 28 *fj* 82	67 74	*f* 10 *fr* 82	... ...	... ...
Reactivity of zinc dust in this medium.	...	...	...	...	50	*jm* 82	...	...	49	*jmq* 721

[1] *See* Table I. for the key to the individual pigments.
[2] In some cases more than one cause is operative, but, for purposes of clarity, only one is indicated.
[3] None in some cases.

(d) *Behaviour of the Paints in* 100% *Phenolic-Resin Varnishes*.— On the whole, the behaviour of the paints in the 100% phenolic-resin varnishes prepared by Bakelite, Ltd., is slightly better than that of the Derby paints.   For instance, the average merit figure for eight paints of the former type is 10·9, as compared with 8·9 for the 77 Derby formulations.   A more rigorous comparison in the case of corresponding paints with the same pigment combinations will be found in Table XIV, but it should be borne in mind when making such comparisons that, apart from the influence exerted by the difference in the medium itself, the pigment-vehicle ratio was substantially different in the two series of paints.

TABLE XIV.—*Comparison of the Derby and the Bakelite Media.*

Pigment Composition.	Paint No.				Merit Figure.			
	Derby Varnish.	100% Phenolic-Resin Varnishes.			Derby Varnish.	100% Phenolic-Resin Varnishes.		
		P.	*Q.*	*R.*		*P.*	*Q.*	*R.*
ab 64 .	2	77	81	83	12	18	14	12 [1]
d 10 .	71	80	...	...	6	8	...	...
dgj 415 .	48	79	82	...	9	5	5	...
dq 82 .	40	78	...	...	9	14	...	...

[1] *ab* 64/*R* for first coat only; second coat *d* 10/*P*.

B.—THE EFFECT OF THE MEDIUM.

(1) *Experimental.*

We now turn to the second part of this investigation, in which the effect of variations in the medium was studied. As already stated, this series of tests was made at Emsworth. In their conduct the authors have had the valued support of Dr. I. G. Slater, Secretary of the Admiralty Corrosion Committee, under whose supervision the whole of the painting and exposure of the specimens was carried out and who has also been responsible for the periodical reports on the condition of the specimens throughout exposure.

(a) *Preparation of the Paints.*—The 63 paints concerned in this investigation were prepared at Derby, one half gallon of each being made. Full details of their formulation and manufacture are given in Appendix F. They comprise the 21 different paint media listed in Table XV., not all of which would normally be considered practicable for the preparation of paints of this class, the exceptions having been included purely for experimental purposes. Each medium was used in the preparation of three paints, pigmented as follows :

(a) With Burntisland red alone (reference *d*).

(b) With a mixture of Burntisland red 6 parts and barytes 4 parts (reference *de* 64).

(c) With a ternary mixture of Burntisland red, barytes and barium chromate in the proportion 6 : 4 : 2 (reference *den* 642).

The preparation of the various media is fully described in Appendix F.

It will be seen from Table XV. that the media can be roughly divided into four classes :

(i) Synthetic-resin media including two phenolic resins, one alkyd resin and three coumarone resins.

(ii) Six different types of oleo-resin varnish medium.

(iii) Five bituminous media.

(iv) Four " sundry " media, *viz.*, aromatic petroleum residue, chlorinated rubber, lanolin and shellac.

A further formulated anti-fouling composition, reference *AF*1/43, was prepared for application over the anti-corrosive paint. Particulars of its formulation will be found in Table IV.

As in the case of the Caernarvon tests, samples of each paint were subjected to storage tests both at Derby and at Woolwich (120° F.) with the results given in Appendix G.

(b) *Preparation of the Specimens.*—In the Emsworth tests the paints were applied to specimens of mild steel, $15 \times 10 \times \frac{1}{8}$ in. in size, cut from ships' plate *ex* H.M. Dockyard stock. These were pickled in cold 15% (by volume) hydrochloric acid containing an inhibitor; after pickling, the plates were weathered outdoors for

TABLE XV.—*List of Media and Paint Numbers.*

No.	Medium. Description.	Paint No.[1]		
		d.	*de* 64.	*den* 642.
	Synthetic-Resin Media.			
2	Modified phenol-formaldehyde/stand-oil	89	90	91
5	Modified cresol-formaldehyde/stand-oil	98	99	100
8	Alkyd + zinc resinate	107	108	109
19	British-coumarone-*A*/litho-varnish	140	141	142
21	British-coumarone-*B*/litho-varnish	146	147	148
17	U.S.A.-coumarone C/litho-varnish	134	135	136
	Oleo-Resin Varnish Media.			
6	Refined-linseed-oil/lime-hardened-rosin	101	102	103
14	Litho-varnish/lime-hardened-rosin	125	126	127
20	Litho-varnish/Congo-ester	143	144	145
4	Litho-varnish/Congo-ester + paraffin wax	95	96	97
11	Litho-varnish/Congo-ester + zinc resinate	116	117	118
12	Tung-oil/lime-hardened-rosin	119	120	121
	Bituminous Media.			
10	Blown bitumen	113	114	115
18	Bitumen	137	138	139
3	Bitumen + ozokerite	92	93	94
7	Bitumen + beeswax	104	105	106
13	Bitumen + paraffin wax	122	123	124
	Sundry Media.			
1	Aromatic petroleum residue	86	87	88
9	Chlorinated rubber	110	111	112
15	Shellac	128	129	130
16	Lanolin	131	132	133

[1] Pigments as follows : *d* Burntisland red; *de* 64 Burntisland red and barytes; *den* 642 Burntisland red, barytes and barium chromate.

30 days, from December 23, 1942, to January 22, 1943. During this period rain fell on 18 days to a total of 4·9 in. The specimens were wire-brushed before painting.

The average loss on pickling was 25·9 g. (range 7–49 g.), the average gain in weight on weathering was 4·3 g. and the average loss in weight after weathering and wire-brushing was 0·84 g. per specimen.[1]

(c) *Painting of the Specimens.*—Each paint was applied to duplicate specimens; 2-in. flat brushes were used, and the painting was carried out by a skilled operator from the Constructive Department, H.M. Dockyard, Portsmouth, and by a member of the Metallurgical Laboratory staff, Engineering Department, H.M. Dockyard, Portsmouth. So far as was practicable, duplicate specimens were painted by different painters, and without exception all the coats on a particular panel were applied by the same painter.

[1] *See* first footnote to Section A, sub-section 1(*b*)(i).

PLATE XXV.

ADMIRALTY CORROSION COMMITTEE EXPOSURE STATION, EMSWORTH, HANTS.

FIG. 1.—Exposure Panel, showing method of suspension.

PLATE XXVI.

ADMIRALTY CORROSION COMMITTEE EXPOSURE STATION, EMSWORTH, HANTS.

FIG. 2.—Portion of Exposure Frame seen at low tide.

FIG. 3.—Disposition of Exposure Frame in Pool. View at half-tide looking south to seaward.

The painting procedure was so arranged that the application of the first anti-corrosive coat to all the specimens was completed before the second anti-corrosive coats were applied. As a result the drying time allowed for the first anti-corrosive coat varied from a minimum of 24 hr. to a maximum of 5 days. Thereafter an interval of 24 hr. was allowed between the second anti-corrosive coat and the final coat of anti-fouling. All the specimens were immersed $4\frac{1}{2}$ hr. after the application of the anti-fouling coat.

Information concerning the painting of each specimen, &c., will be found in Appendix H. A summary of the data as a whole is given in Table XVI.

TABLE XVI.—*Painting of the Specimens. Series* B. *Emsworth.*

	Number of Observations.	Max.	Min.	Mean.	Standard Deviation.	90% Range.[2]
Atmospheric temp. ° F..	36	53	38	46	...	...
Relative humidity. % .	36	100	79	86	...	...
Spreading rate of paints. Sq. yd. per gal. : [1]						
1st coat. *AC1* . .	126	241	63	123	33	178–68
2nd coat. *AC2* . .	63	179	59	105	25	146–64
3rd coat. *AF3* . .	63	84	56	70	7	82–58

[1] Calculated from the mean value of the weights of wet paint for each pair of specimens, except for the first coat where the values for individual specimens have been used.
[2] Approximate limiting values containing 90% of the observations calculated as the mean value $\pm$ 1.645 times the standard deviation.

(d) *Method of Exposure.*—The method of exposure used at the Admiralty Corrosion Committee's testing station at Emsworth will be clear from Figs. 1, 2 and 3. Each specimen is suspended by means of two hooks of $\frac{1}{4}$-in. dia. mild-steel rod from horizontals of $1\frac{1}{2} \times \frac{1}{4}$-in. angle steel, carried on a steel framework resting on the bed of a swimming pool. The specimens are secured to the hooks by mild-steel nuts and washers; the whole of these parts together with the hooks are coated with an efficient anti-corrosive paint followed by the same anti-fouling composition as that used on the specimens (*see* Fig. 1).

Each horizontal is 19 ft. 8 in. long and will carry 14 specimens of the standard size, allowing a 6-in. gap between each. The whole frame comprises 17 of these horizontals at 20 in. apart, thus providing a maximum capacity of 238 specimens (*see* Fig. 2). The horizontals run due north and south and the plates are hung with the fronts facing east.

The frame (suitably protected with bituminous paint) is situated in the south-east corner of the pool about 6 ft. from the southern and eastern walls (*see* Fig. 3). Contact between the water in the pool and the sea is made at each high tide by a non-return valve situated in the bottom of the wall at the south-east corner; in addition, at each tide (with the exception of three or four neaps) the

sea washes over the wall and floods the whole pool. The depth of water over the top edges of the specimens is approximately 10 in. at low tides, reaching approximately 1 ft. 6 in. at high neap tides and 3 ft. 6 in. at high spring tides.

(e) *Inspections during Exposure.*—The specimens were immersed at various dates between February 8 and 12, 1943, and were inspected at six-weekly intervals by members of Dr. Slater's staff. Four inspections in all were made up to and including July 29, 1943, on which date all specimens were removed, cleaned, reweighed and forwarded to Birmingham for the final examination.

(f) *Final Examination in the Laboratory.*—The final examination in the laboratory was conducted on exactly the same lines as for the Caernarvon series (*see* Section A, sub-section 1(f)).

(2) *Results.*

(a) *Visual Inspection—Fouling.*—The conditions of exposure in the Emsworth swimming pool differ somewhat from those beneath the Caernarvon raft. Except for the rise and fall of the water in the pool with the tides, there is no tidal current transversely to the specimens, and breakdown takes a rather different form, the edge effect, *i.e.*, failure by blistering and flaking from the edges inwards, being more pronounced than at Caernarvon. Conditions in the pool proved only moderately severe as regards fouling. In fact, at the last inspection (after 24 weeks) in July, 1943, the majority of the specimens were free from all fouling other than slime; the remainder had relatively light deposits of grass or shell (barnacles).[1]

(b) *Relative Behaviour of the Anti-Corrosive Compositions.*—The same data are available for all test specimens as in the case of the

TABLE XVII.—*Classification Limits. Series* B. *Emsworth.*

Grade.				Score.	Limits.	
					Index Figure at 24 Weeks.[1]	Rusting.[2]
Very good	.	.	.	3	0–15	0–3
Good	.	.	.	2	16–39	4–9
Moderate	.	.	.	1	40–79	10–19
Bad	.	.	.	0	80 and over	20 and over

[1] Here the index figure is based on the observations at 24 weeks alone and is not the cumulative sum for all inspections as in Table VI. The different method of computation has no practical effect on the results.
[2] Sum of area rusted (%) on both front and back surfaces.

Caernarvon series (*see* Section A, sub-section 2(b)). It is considered desirable, however, in this case to ignore the changes in weight on exposure and the estimates of the percentage of intact paint left

[1] It should be noted that, although the anti-fouling paint $AF1/43$ used in these tests was an improvement on that used at Caernarvon ($AF8/42$), the former is to be regarded as unsatisfactory.

TABLE XVIII.—Results of Emsworth Tests on the Effect of Different Media in Anti-Corrosive Compositions.

No.	Medium. Designation.	Gradings.[1] Index Figure. d. 1.	d. 2.	de 64. 3.	de 64. 4.	den 642.[2] 5.	den 642.[2] 6.	Rusting. d. 1.	d. 2.	de 64. 3.	de 64. 4.	den 642.[2] 5.	den 642.[2] 6.	Total (Merit Figure).	Storage Properties.[1],[3]
	Synthetic–Resin Media.														
2	Modified phenol-formaldehyde/stand-oil	1	1	1	1	2	1	3	3	3	2	3	2	23	M
5	Modified cresol-formaldehyde/stand-oil	2	2	3	2	1	2	3	3	3	3	3	3	30	B
8	Alkyd + zinc resinate	0	0	0	0	1	2	1	1	2	2	3	3	15	G
19	British-coumarone-A/litho-varnish	1	1	1	1	2	2	3	3	3	3	3	3	26	B
21	British-coumarone-B/litho-varnish	1	0	0	0	1	1	3	2	1	0	2	3	14	B
17	U.S.A.-coumarone C/litho-varnish	1	0	0	0	1	2	3	2	1	0	3	3	16	M
	Oleo–Resin Varnish Media.														
6	Refined-linseed-oil/lime-hardened-rosin	0	0	0	0	0	0	0	1	0	0	0	0	1	G
14	Litho-varnish/lime-hardened-rosin	0	0	0	0	0	0	0	0	1	1	1	0	3	G
20	Litho-varnish/Congo-ester	1	0	0	0	0	0	1	1	0	0	0	1	4	B
4	Litho-varnish/Congo-ester + paraffin wax	0	0	0	0	0	0	1	1	0	0	1	0	3	M
11	Litho-varnish/Congo-ester + zinc resinate	0	0	0	0	0	0	1	1	0	0	0	1	3	B
12	Tung-oil/lime-hardened-rosin	1	0	0	0	1	0	2	2	0	2	2	1	11	G
	Bituminous Media.														
10	Blown bitumen	0	0	0	0	0	0	2	2	2	1	2	1	10	M
18	Bitumen	0	0	0	0	1	0	2	1	2	2	2	2	12	B
8	Bitumen + ozokerite	0	0	0	0	1	0	2	2	2	1	2	1	11	B
7	Bitumen + beeswax	0	0	1	0	0	0	2	2	2	2	2	2	13	B
13	Bitumen + paraffin wax	0	0	0	0	0	0	0	0	0	0	0	0	0	B
	Sundry Media.														
1	Aromatic petroleum residue	0	0	0	0	0	0	2	0	0	0	0	0	2	G
9	Chlorinated rubber	0	0	1	2	2	2	2	2	3	3	3	3	23	M
15	Shellac	1	0	0	0	0	0	2	2	2	2	1	1	11	G
16	Lanolin	0	0	0	0	0	0	0	0	0	0	0	0	0	B
	Totals	9	4	7	6	13	12	35	31	27	24	33	30	231	
			13		13		25		66		61		63		

[1] 3 = V = very good; 2 = G = good; 1 = M = moderate; 0 = B = bad. [2] See footnote 1 to Table XV.

[3] A joint assessment for all three paints in the same medium based on the detailed results given in Appendix G.

after test, since, owing to certain complicating factors (*e.g.*, the attack at the edges and the high staining power of the Burntisland-red pigment used), these data are erratic. The assessment of the relative merits of the different media will, therefore, be based on two sets of observations :

(i) The index figure at the last inspection after 24 weeks.

(ii) The percentage area observed to be rusted in the final laboratory inspection.

As before, each specimen has been classed as very good, good, moderate or bad, the classification limits in each respect being shown in Table XVII. Results obtained in this way are grouped in Table XVIII. for all six specimens coated with paints in the same medium, the maximum possible merit figure being 36. A more detailed statement of the results will be found in Appendix J.

(3) *Discussion of Results.*

(a) *The Best Anti-Corrosive Media.*—A list of the eight best media in these tests is given in Table XIX. Too much attention should

TABLE XIX.—*List of the Best Media in the Emsworth Tests.*

Merit Figure.	Medium.		Storage Properties.
	No.	Description.	
30	5	Modified cresol-formaldehyde/stand-oil.	Bad
26	19	British-coumarone-*A*/litho-varnish.	Bad
23	9	Chlorinated rubber.	Moderate
23	2	Modified phenol-formaldehyde/stand-oil.	Moderate
16	17	U.S.A. coumarone-*C*/litho-varnish.	Moderate
15	8	Alkyd + zinc resinate.	Good
14	21	British-coumarone-*B*/litho-varnish.	Bad
13	7	Bitumen + beeswax.	Bad

not be paid to minor differences in the merit figure of individual media, but it is fair to conclude that the first four media are superior to the others. They are a modified cresol-formaldehyde/stand-oil varnish, a coumarone/litho varnish, a chlorinated rubber and a modified phenol-formaldehyde/stand-oil varnish. As regards the three coumarone/litho-varnish media, all of which appear on this short list, it should be noted that the formulations are identical, save that the resins were obtained from three different sources. A satisfactory feature of the results from the British point of view is that the home-produced resins have proved at least as serviceable as the imported product.

(b) *Comparison of the Three Different Pigments.*—It would seem from the total merit figures for each of the three groups of 21 paints pigmented in the same way (Table XVIII.) that, apart from an indication of some slight superiority as regards the index figure after 24 weeks in the case of the Burntisland red, barytes and barium

chromate mixture, there is little to choose between the three pigmentations.

C.—GENERAL CONCLUSIONS.

It is unnecessary to add much to the exposition of the results given in the previous Sections of this paper. The authors are conscious that the work reported here, although extensive, is far from covering the whole field. Yet a broad survey of the results may be said to indicate clearly the line of development that will lead to marked improvements in anti-corrosive compositions for ships' bottoms and underwater use on steel generally. This will consist in incorporating various inhibitive pigments, of which basic lead sulphate has been shown to be one of the most promising, in one or more of a range of synthetic media, such as the various phenolic- or coumarone-resin varnishes and chlorinated rubber included in the present investigations, to which list there may well prove to be further additions. A number of possible combinations will readily suggest themselves to those who study the results in detail. The authors, for their part, have drawn up and are implementing, on behalf of the Marine Corrosion Sub-Committee, a further series of tests on 127 formulated anti-corrosive compositions selected systematically on the basis of the present results. They hope that these will lead to further improvements in performance. Raft tests on the new compositions have already been begun and will be combined with practical tests on ships' bottoms; a number of tests of the latter type are now in progress on paints of the earlier series. It is hoped that this combination of experimental methods, coupled with the Sub-Committee's investigations of anti-fouling compositions, which are being actively prosecuted under the direction of Dr. J. E. Harris, will result in the establishment within not too long a period of the best practicable formulations of painting schemes for use on ships' bottoms.

Two final observations :

(i) It is an interesting fact that most of the authors' findings, as regards both the pigmentation and the choice of media for anti-corrosive compositions, are in substantial agreement with the views of their scientific colleagues in the United States.[1]

(ii) For practical progress improvements in the conditions under which paints are applied to ships' hulls on the slips or in dry-dock must be made *pari passu* with improvements in the formulation of the anti-corrosive paints themselves. The facts that in Great Britain rain falls on one day out of three and that our winter months are damp and humid cannot be ignored. Under adverse conditions of application the difference between the best and worst paints may become insignificant. Thus, another necessary subject of research, to which the Marine Corrosion Sub-Committee are paying due attention, is how to render a paint less sensitive to the handicap of

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[1] *See*, for instance, F. N. Speller, "Recent Developments in Underwater Paints and Coatings," "Third Water Conference," p. 17. Pittsburgh, Pa., U.S.A., 1943 : Engineers' Society of Western Pennsylvania.

adverse weather conditions at the time of application, either by modifying the formulation of the paint itself or by developing suitable methods of surface treatment. It may well be found at no great distance in the future that the solution of the problem, so far as new construction is concerned, has been facilitated by the introduction of prefabrication methods in which large areas of plating are assembled in one unit before leaving the shops. Presumably, should it be so desired, there would be little difficulty in arranging that the initial painting of these units should also take place in good conditions under cover.

APPENDIX A.—*Formulation of Paints Nos. 1 to 75, 84 and 85 and Compositions of Pigments Used.*

The formulation of paints Nos. 1–75, 84 and 85 is recorded in Table XX., and the compositions of the pigments used are stated in Table XXI.

TABLE XX.—*Formulation of Paints Nos. 1–75, 84 and 85.*

Paint No.:	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.
Pigmentation:	a 10.	ab 64.	ab 37.	af 28.	ak 28.	ah 28.	ad 28.	ap 73.	ae 73.	ac 28.	abp 643.	ahp 283.	adp 283.
Pigment.													
a. Red lead. %	82·6	46·5	25·5	12·0	13·5	15·9	13·9	56·6	55·1	17·0	37·3	12·5	10·8
b. White lead. %	...	27·0	50·8	...	...	...	...	...	...	59·1	21·1	...	...
c. Basic lead sulphate. %	...	...	...	...	...	...	48·5	...	...	...	...	...	36·7
d. Burntisland red. %	...	...	...	...	...	...	...	...	...	...	...	...	...
e. Barytes. %	...	...	...	...	...	...	...	...	20·6	...	...	...	...
f. Graphite. %	...	...	...	41·7	...	...	...	...	...	...	...	...	...
h. Red oxide. %	...	...	...	...	46·9	55·2	...	...	...	...	...	43·3	...
k. Bideford black. %	...	...	...	...	...	...	...	...	...	...	16·5	...	14·3
p. Witherite. %	...	...	...	...	...	...	...	21·4	...	...	2·5	16·5	3·3
u. Asbestine. %	...	...	...	...	...	...	3·8	2·2	2·3	...	2·5	...	3·3
Medium.													
Varnish, *see text*. %	10·4	13·8	15·4	32·6	27·5	20·7	23·8	13·0	15·2	16·6	14·0	19·3	26·8
Naphtha. %	6·3	12·0	7·6	10·4	10·5	7·2	8·7	6·1	6·0	7·3	7·8	7·4	6·9
Dipentene. %	0·7	0·7	0·7	...	...	1·0	1·3	0·7	0·8	...	0·8	1·0	1·2
Drier.													
Lead-cobalt naphthenates. %	...	...	...	3·3	1·6	...	...	...	...	...	...	...	...
Total volatile matter. %	11·1	18·2	14·4	23·4	21·5	16·6	19·5	12·0	12·9	13·8	14·2	16·1	13·8
Ford cup efflux time.[1] Sec.	29	...[2]	...[2]	90	75	28	44	18	18	12	...[2]	14	43
Specific gravity	3·56	2·77	3·00	1·48	1·50	2·96	1·88	3·10	3·00	2·96	2·89	2·60	2·30

[1] Efflux time of the first 50 c.c. from a full No. 4 Ford cup at 70° F.
[2] No figures available as the paints required additional thinning at Caernarvon prior to application. The composition given is that of the paint as applied.

TABLE XX.—(Continued.)

Paint No.:	14.	15.	16.	17.	18.	19.	20.	21.	22.	23.	24.	25.	26.
Pigmentation :	acp 283.	ace 283.	abf 238.	abd 238.	abc 238.	adk 244.	ack 244.	acd 244.	adg 181.	b 10.	bf 28.	bk 28.	bh 28.
Pigment.													
a. Red lead. %	12·7	12·4	10·0	10·8	13·4	13·9	14·6	14·7	6·5	…	…	…	…
b. White lead. %	…	…	13·2	14·3	17·5	…	…	…	…	77·7	10·5	11·9	14·1
c. Basic lead sulphate. %	44·2	43·2	…	…	46·6	…	25·4	25·7	…	…	…	…	…
d. Burntisland red. %	…	…	34·6	37·8	…	24·2	…	25·6	45·5	…	…	…	…
e. Barytes. %	…	16·4	…	…	…	…	…	…	…	…	…	…	…
f. Graphite. %	…	…	…	…	…	…	…	…	…	…	42·3	…	…
g. Aluminium. %	…	…	…	…	…	…	…	…	5·6	…	…	…	…
h. Red oxide. %	…	…	…	…	…	…	…	…	…	…	…	…	56·2
k. Bideford black. %	…	…	…	…	…	24·2	26·2	…	…	…	…	47·5	…
p. Witherite. %	16·8	…	…	…	…	…	…	2·2	…	…	…	…	…
u. Asbestine. %	1·7	1·8	…	…	…	…	…	…	…	0·3	…	…	…
Vegetable black. %	…	…	…	…	…	…	…	…	…	…	…	…	…
Medium.													
Varnish, see text. %	16·6	18·2	29·8	26·4	16·4	28·0	23·9	23·1	32·5	15·7	33·4	28·3	21·6
Naphtha. %	7·1	7·1	9·7	6·4	6·1	8·9	9·0	7·6	8·0	5·5	10·5	10·6	7·1
Dipentene. %	0·9	0·9	…	1·1	…	…	…	1·1	1·5	0·8	…	…	1·0
Drier.													
Lead-cobalt naphthenates. %	…	…	2·7	…	…	0·8	0·9	…	0·4	…	3·3	1·7	…
Total volatile matter. %	14·6	15·3	21·6	18·1	12·6	20·9	18·6	17·9	22·5	12·6	23·8	21·9	16·7
Ford cup efflux time.¹ Sec.	8½	11¼	63	46	12	59	27	28	54	12	96	72	18
Specific gravity	2·66	2·70	1·60	2·00	2·90	1·76	1·90	2·14	1·68	3·00	1·46	1·50	2·48

¹ Efflux time for first 50 c.c. from a full No. 4 Ford cup at 70° F

TABLE XX.—(*Continued.*)

Paint No. :	27.	28.	29.	30.	31.	32.	33.	34.	35.	36.	37.	38.	39.
Pigmentation :	*bd* 28.	*bc* 28.	*bde* 283.	*bdf* 244.	*bcf* 244.	*bcd* 244.	*bij* 82.	*ig* 82.	*din* 82.	*cn* 82.	*den* 832.	*cen* 832.	*fg* 82.
Pigment.													
b. White lead. %	11·5	14·8	9·0	11·4	12·4	13·6	58·4						
c. Basic lead sulphate. %		59·0			24·8	27·2				57·3		44·0	
d. Burntisland red. %	46·1		36·1	23·1		27·3			44·8		34·6		
e. Barytes. %			13·5								13·0	16·5	
f. Graphite. %				23·7	24·8								39·1
i. Zinc oxide. %							14·6	40·8	11·2				
n. Barium chromate. %									3·9	14·3	8·6	10·8	
g. Zinc chromate. %								10·2					9·8
u. Asbestine. %	4·1		4·3								4·1		
Vegetable black. %		0·4					0·4						
Medium.													
Varnish, *see text.* %	28·9	18·4	27·6	31·0	26·8	23·5	18·8	34·7	30·9	20·1	28·6	20·6	26·7
Naphtha. %	8·1	7·4	8·3	9·0	9·2	7·2	7·4	10·7	7·6	7·8	9·5	7·8	11·2
Dipentene. %	1·3		1·2			1·2			1·2		1·3		
Drier.													
Lead-cobalt naphthenates. %				1·8	2·0		0·4	3·6	0·4	0·5	0·3	0·3	3·2
Total volatile matter. %	21·0	14·7	20·5	21·4	19·9	17·8	14·9	24·6	21·2	15·8	22·2	16·0	25·9
Ford cup efflux time.[1] Sec.	29	14	32	75	42	41	26	85	52	13	36	18	93
Specific gravity	1·80	2·74	1·85	1·62	1·80	2·16	2·64	1·42	1·78	2·48	1·82	2·52	1·36

[1] Efflux time for first 50 c.c. from a full No. 4 Ford cup at 70° F.

TABLE XX.—(Continued.)

Paint No.	40.	41.	42.	43.	44.	45.	46.	47.	48.	49.	50.	51.	52.
Pigmentation :	dq 82.	cq 82.	fs 82.	ds 82.	fj 82.	jk 28.	cj 82.	cej 832.	dgj 415.	jmq 721.	fm 82.	dfj 73.	g 10.
Pigment.													
c. Basic lead sulphate, %	…	55·1	…	…	…	…	55·6	42·8	…	…	…	…	…
d. Burntisland red. %	43·4	…	…	44·1	…	…	…	…	22·3	…	…	39·2	…
e. Barytes. %	…	…	40·5	…	40·4	…	…	16·0	…	…	…	…	…
f. Graphite. %	…	…	…	…	…	…	…	…	…	…	49·8	…	…
g. Aluminium. %	…	…	…	…	…	…	…	…	5·6	…	…	…	35·3
j. Zinc oxide. %	…	…	…	…	10·1	11·3	13·9	10·7	28·0	43·5	…	16·8	…
k. Bideford black. %	…	…	…	…	…	45·2	…	…	…	…	…	…	…
m. Zinc dust. %	…	…	…	…	…	…	…	…	…	12·4	12·4	…	…
q. Zinc chromate. %	10·8	13·8	…	11·0	…	…	…	…	…	6·2	…	…	…
s. Chromated zinc. %	3·8	…	10·1	3·9	…	…	0·5	0·4	…	…	…	3·5	…
u. Asbestine. %	…	…	…	…	…	…	…	…	…	…	…	…	…
Vegetable black. %	…	…	…	…	…	…	…	…	…	…	0·3	…	…
Medium.													
Varnish, see text. %	32·0	22·1	34·0	30·1	34·4	29·6	20·7	21·0	31·5	24·4	24·1	29·9	48·2
Naphtha. %	8·6	8·7	11·9	9·1	11·6	12·0	8·8	8·8	11·1	11·8	11·6	8·7	12·5
Dipentene. %	1·2	…	…	1·4	…	…	…	…	…	…	…	1·4	…
Drier.													
Lead-cobalt naphthenates. %	0·2	0·3	3·5	0·4	3·5	1·9	0·5	0·3	1·5	1·7	1·8	0·5	4·0
Total volatile matter. %	22·6	17·5	25·5	22·9	25·4	23·8	17·1	17·2	23·7	21·5	21·2	22·1	31·8
Ford cup efflux time.[1] Sec.	55	15	125	71	108	75	18	17½	33	21	52	60	69
Specific gravity	1·74	2·36	1·36	1·70	1·40	1·42	2·44	2·40	1·64	1·98	2·02	1·76	1·16

[1] Efflux time for first 50 c.c. from a full No. 4 Ford cup at 70° F.

TABLE XX.—(Continued.)

Paint No.: Pigmentation:	53. gh 28.	54. dg 82.	55. cg 82.	56. egh 328.	57. deg 832.	58. ceg 832.	59. gj 82.	60. lim 82.	61. dm 82.	62. cm 82.	63. ehm 382.	64. dem 832.	65. cem 832.
Pigment.													
c. Basic lead sulphate. %	…	…	48·7	…	…	38·6	…	…	…	60·1	…	…	44·4
d. Burntisland red. %	…	40·8	…	…	31·2	…	…	…	48·0	…	…	37·6	…
e. Barytes. %	…	…	…	14·0	11·7	14·5	…	…	…	…	15·6	14·2	16·6
g. Aluminium. %	11·4	10·2	12·2	9·3	7·8	9·7	30·7	…	…	…	…	…	…
h. Red oxide. %	45·7	…	…	37·2	…	…	…	54·0	…	…	41·6	…	…
j. Zinc oxide. %	…	…	…	…	…	…	7·7	…	…	…	…	9·4	11·1
m. Zinc dust. %	…	…	…	…	3·8	…	…	13·5	12·0	15·0	10·4	…	…
u. Asbestine. %	…	…	…	…	…	…	…	2·6	2·5	0·2	2·6	3·1	2·1
Vegetable black. %	…	…	…	…	…	…	…	…	…	…	…	…	…
Medium.													
Varnish, see text. %	31·0	35·4	28·3	29·4	33·1	27·0	45·2	21·5	28·6	17·4	22·6	27·5	18·6
Naphtha. %	9·1	10·9	9·4	9·0	10·0	9·1	12·7	7·3	7·5	7·1	7·1	6·8	7·1
Dipentene. %	1·5	1·7	…	…	1·5	…	…	0·9	1·3	…	…	1·3	…
Drier.													
Lead-cobalt naphthenates. %	1·3	1·0	1·4	1·1	0·9	1·1	3·7	0·2	0·1	0·2	0·1	0·1	0·1
Total volatile matter. %	23·0	26·8	20·7	20·7	24·7	19·9	30·8	16·8	20·2	14·0	16·1	19·1	14·5
Ford cup efflux time.[1] Sec.	18	38	21	17	39	20	49	27	57	11	35	60	14
Specific gravity	1·76	1·50	1·90	1·66	1·62	1·96	1·26	2·44	1·86	2·84	2·40	1·94	2·68

[1] Efflux time for first 50 c.c. from a full No. 4 Ford cup at 70° F]

TABLE XX.—(Continued.)

Paint No.:	66.	67.	68.	69.	70.	71.	72.	72A.	73.	74.	75.	84.	85.
Pigmentation:	c 10.	f 10.	fk 82.	afk 282.	fkn 822.	d 10.	h 10.	h 10.	t 10.	fr 82.	dr 82.	fr 13.	jq 3/11.
Pigment.													
a. Red lead. %	…	…	…	10·1	…	…	…	…	…	…	…	…	…
c. Basic lead sulphate. %	74·3	…	…	…	…	…	…	…	…	…	…	…	…
d. Burntisland red. %	…	…	…	…	…	54·8	…	…	…	…	42·3	…	…
f. Graphite. %	…	48·7	40·0	35·1	34·5	…	…	…	…	38·0	…	12·2	…
h. Red oxide. %	…	…	…	…	…	…	68·6	62·7	…	…	…	…	…
j. Zinc oxide. %	…	…	…	…	…	…	…	…	…	…	…	…	12·2
k. Bideford black. %	…	…	10·0	8·8	8·6	…	…	…	…	…	…	…	…
n. Barium chromate. %	…	…	…	…	8·6	…	…	…	…	…	…	…	…
q. Zinc chromate. %	…	…	…	…	…	…	…	…	…	…	…	…	44·0
r. Zinc tetrahydroxy-chromate. %	…	…	…	…	…	4·7	…	…	…	9·5	10·6	36·8	…
t. Lithopone. %	…	…	…	…	…	…	…	…	68·4	…	3·7	…	…
u. Asbestine. %	…	…	…	…	…	…	…	…	0·5	…	…	…	…
Vegetable black. %	…	…	…	…	…	…	…	…	…	…	…	…	…
Medium.													
Varnish, see text. %	17·8	36·3	35·2	32·3	34·2	31·9	23·8	30·3	22·3	36·3	32·2	37·2	30·0
Naphtha. %	7·9	11·2	11·3	10·6	10·8	8·6	7·6	7·0	7·8	12·4	8·8	13·8	13·8
Dipentene. %	…	…	…	…	…	…	…	…	…	…	1·5	…	…
Drier.													
Lead-cobalt naphthenates. %	…	3·8	3·5	3·1	3·3	…	…	…	1·0	3·8	0·9	…	…
Total volatile matter. %	15·0	25·7	25·4	23·5	24·6	21·3	17·1	19·1	16·7	26·9	23·1	28·7	25·8
Ford cup efflux time.[1] Sec.	11	140	103	97	84	52	14	…[a]	32	165	109	…	…
Specific gravity	2·76	1·32	1·34	1·46	1·40	1·78	2·42	2·06	2·00	1·34	1·64	1·50	1·74

[1] Efflux time for first 50 c.c. from a full No. 4 Ford Cup at 70° F.   [a] Not determined.

TABLE XXI.—*Compositions of Pigments.*

Pigment.	Complies with B.S.S. No.—	Additional Information.
a. Red lead, non-setting.	217/1936, Type *A*.	97·0% Pb_3O_4.
b. White lead.	239/1935	77·2% $PbCO_3$, 22·6% $Pb(OH)_2$.
c. Basic lead sulphate.	637/1935	74·7% $PbSO_4$, 22·1% PbO, 1·2% ZnO.
d. Burntisland red.[1,2]	...	46·0% Fe_2O_3.
e. Barytes.[1]	...	66·4% $BaSO_4$.[3]
f. Graphite.	...	85·0% graphitic carbon.
g. Aluminium powder.	388/1938	Passes 200 I.M.M. standard screen.
h. Red oxide.	305/1936, Type 1.	97·2% Fe_2O_3.
j. Zinc oxide.	254/1935, Type 1, Grade *L*.	99·4% ZnO.
k. Bideford black.	288/1937	55·7% ash.
m. Zinc dust.	...	97·2% Zn, 1·9% ZnO.
n. Barium chromate.[1]	...	36·5% CrO_3, 57·2% BaO.
p. Witherite.	926/1940	95·0% $BaCO_3$.
q. Zinc chromate.	389/1938	41·2% CrO_3, 38·4% ZnO.
r. Zinc tetrahydroxy-chromate.	...	15·2% CrO_3, 64·1% ZnO.[4]
s. Chromated zinc oxide.	...	5·0% CrO_3, 88·0% ZnO.
t. Lithopone.	296/1935	31·1% ZnS, 1·1% ZnO.
u. Asbestine.	255/1938	

[1] These pigments were also used for the preparation of the Emsworth paints.
[2] Burntisland red is the iron-oxide pigment left after the recovery of aluminium from bauxite.
[3] Hopton barytes.
[4] Approximates to $ZnCrO_4,4Zn(OH)_2$.

APPENDIX B.—*Details of Paints Nos.* 76 *to* 83 *in* 100% *Phenolic-Resin Media.*

(1) *Paint Formulations.*—Full details of the formulations of the paints in 100% phenolic-resin media prepared by Bakelite, Ltd., are given in Table XXII. All of them were ground in ball mills with steel balls for 24 hr. Where guaiacol was used it was added after grinding, dissolved in the mixed xylol and butyl alcohol. In those paints containing aluminium powder this was added after grinding and stirred in.

(2) *Media.*—The following details concerning the preparation of the media complete the more general information summarised in Table III. of the main text.

(a) *Varnish* P.

Formula.—Bakelite resin No. *R.*254 . . 20·4%
Tung oil . . . . 20·0%
Varnish linseed oil . . . 19·8%
White spirit . . . . 28·5%
Xylol . . . . . 5·9%
Dipentene . . . . 5·4%
(Non-volatile content . . 60%)

Process.—Raise linseed oil and half the resin to 293° C. in 30 min. and hold 60 min. to a long string. Check with remainder of the resin, dissolve and add tung oil. Raise to 240° C. and hold for about 30 min. to a heavy drip from puddle. Cool and thin.

TABLE XXII.—*Formulations of the Paints in 100% Phenolic-Resin Media.*[1]

	Medium P.										Medium Q.				Medium R.
Paint No.	76/1.	76/2.	77/1.	77/2.	78/1.	78/2.	79/1.	79/2.	80/1.	80/2 & 83/2.	81/1.	81/2.	82/1.	82/2.	83/1.
Pigmentation :	qu 41.	qu 41.	ab 32.	ab 32.	dq 41.	dq 41.	dqj 415.	dqj 415.	d 10.	d 10.	ab 32.	ab 32.	dqj 415.	dqj 415.	ab 32.
Medium. Varnish, *see text*. %	44·8	39·0	46·9	41·0	44·3	39·0	45·0	38·0	45·5	41·0	49·0	41·1	46·4	43·1	47·9
Pigment.															
a. Red lead, %			25·3	29·6							26·5	29·6			29·0
b. White lead, %			16·9	19·7							17·7	19·8			19·1
d. Burntisland red, %					31·9	37·5	16·2	18·2	41·0	49·2			16·7	20·7	
g. Aluminium, %															
j. Zinc oxide, %							4·1	4·6					4·2	5·2	
q. Zinc chromate, %	32·3	37·4			8·0	9·4	20·3	22·8					20·9	25·9	
u. Asbestine, %	8·1	9·3													
Thinners.															
White spirit, %	14·3	13·9	10·8	9·4	15·5	13·9	14·4	16·3	13·2	9·7	6·9	9·5	11·8	5·2	3·8
Xylol, %	0·1	0·1	0·1	0·1	0·1	0·1			0·1	0·1					0·1
Butyl alcohol, %	0·1	0·1	0·1	0·1	0·1	0·1			0·1	0·1					0·1
Guaiacol. %	0·1	0·1	0·1	0·1											
Driers. Pb–Co–Mn naphthenates. %	0·2	0·1			0·2	0·1	0·2	0·1	0·2	0·1					
Total volatile matter	32·4	29·6	29·7	26·1	33·3	29·6	32·4	31·4	31·6	26·7	26·1	25·6	30·0	22·1	19·2
Efflux time.[2] Sec.	26	25	35	36	33	41	27	27	24	26	28	26	26	31	35
Specific gravity	1·28	1·34	1·41	1·59	1·28	1·38	1·25	1·29	1·27	1·36	1·44	1·66	1·29	1·40	1·40

[1] Slight differences were made in the formulations of the first and second coats, which are denoted thus : 76/1, 76/2, &c.
[2] Efflux time of the first 50 c.c. from a full No. 4 Ford cup at 70° F.

(b) *Varnish* Q.

Formula.—Bakelite resin No. R.10840 . . 12·1%
        Tung oil . . . . . 47·1%
        Lead naphthenate . . . 1·0%
        White spirit . . . . 39·2%
        Lead-cobalt naphthenates . . 0·66%
        (Non-volatile content . . 61%)

Process.—Heat resin and oil to 250° C. in 50 min. and hold to a 4-in. string (approximately 10 min.). Cool to 140° C. and stir in lead naphthenate, thin and add driers in solution.

(c) *Varnish* R.

Formula.—Bakelite resin No. R.254 . . 22·6%
        Varnish linseed oil . . . 45·2%
        White spirit . . . . 31·7%
        Lead-cobalt-manganese naphthe-
          nates . . . . . 0·45%
        (Non-volatile content . . 68%)

Process.—Heat resin and oil to 293° C. in approximately 50 min. and hold at this temperature to give 6-in. string when sampled on cold glass plate. Cool and thin, and add driers in solution.

APPENDIX C.—*Physical Properties and Results of Storage Tests. Paints Nos. 1 to 85 and* AF8/42.

The physical properties of the 85 anti-corrosive paints and of the anti-fouling paint prepared for the Caernarvon tests are summarised in Table XXIII., together with the results of the storage tests made on them. The following points should be noted.

(a) *Efflux Time* (*Ford Cup*).—The measurements were made in a constant-temperature chamber at 70° F., the time of efflux of the first 50 c.c. from a No. 4 Ford cup full of the paint being determined.

(b) *Specific Gravity.*—The measurements were made at 70° F. concurrently with the determinations of efflux time by running out the paint from the Ford cup into a tared brass cylinder.

(c) *Drying Time.*—This was taken as the time required for the film to become dry to the touch in a brushing-out test on a steel panel.

(d) *Storage Tests.*—These were made on separate 1-pint tins stored respectively at Derby for 9 months (September, 1942, to June, 1943) and at Woolwich for 6 months under tropical conditions (120° F.).[1] A void space of about 1 in. was left at the top of each tin, which was sealed with a 1½-in. Farwig cap. A number of tins burst or failed during storage at Woolwich, as indicated in Table XXIII. At the end of the storage period the condition of the paint in the tin was noted, *e.g.*, as regards freedom from settling, gelling, &c., the ease with which it could be remixed was determined, and,

[1] Together with 3 months' storage at Derby to complete the full 9-months' nterval between making the paints and testing them.

TABLE XXIII.—*Physical Properties and Results of Storage Tests.   Paints Nos. 1 to 85 and AF8/42.*

No.	Pigment.[1]	Sp. Gr. at 70° F.[2]	Volatile Thinner. %.[3]	Drying Time. Min.[2]	Efflux Time.[4,5] Sec. I.	D.	W.	Condition in Tin D.	W.	Remixing D.	W.	Application D.	W.
1	a 10	3·56	11·1	25	29	—	—	B	B	—	—	—	—
2	ab 64 [6]	2·77	18·2	...	420	—	—	G	B	P	—	—	—
3	ab 37 [6]	3·00	14·4	...	49	—	—	G	B	P	G	P	M
4	af 28	1·48	23·4	135	90	115	—	G	G	P	G	P	M
5	dk 28	1·50	21·5	135	75	300	—	G	G	P	G	G	M
6	ah 28	2·96	16·6	45	28	24	119	G	M	G	M	P	G
7	ad 28	1·88	19·5	65	44	—	—	M	B	—	B	P	—
8	ap 73	3·10	12·0	65	18	—	—	B	B	—	B	P	—
9	ae 73	3·00	12·9	50	18	—	—	B	B	—	—	—	—
10	ac 28	2·96	13·8	55	12	—	—	M	B	—	—	—	—
11	abp 643 [6]	2·89	14·2	...	35	—	—	M	B	B	—	—	—
12	ahp 283	2·60	16·1	55	14	14	—	B	B	B	—	P	—
13	adlp 283	2·00	18·8	65	48	—	—	B	B	—	—	—	—
14	acp 283	2·66	14·6	60	9	12	—	M	B	M	—	P	—
15	ace 283	2·70	15·3	55	12	13	—	M	B	M	—	P	—
16	abf 238	1·60	21·6	125	63	275	315	G	G	P	P	G	G
17	abd 238	2·00	18·1	60	46	210	—	M	M	M	B	G	—
18	abc 238	2·90	12·6	60	12	20	—	M	B	M	—	P	—
19	adk 244	1·76	20·9	70	59	>600	—	V	G	P	G	G	M
20	ack 244	1·90	18·6	60	27	90	360	G	M	V	M	P	G
21	acd 244	2·14	17·9	60	28	—	—	G	G	G	M	G	M
22	adg 181	1·68	22·5	70	54	—	—	M	B	G	—	P	—
23	b 10	3·00	12·6	60	12	—	—	P	B	—	—	—	—
24	bf 28	1·46	23·8	135	96	>600	140	V	G	P	G	P	P
25	bk 28	1·50	21·9	60	72	85	121	G	G	P	G	P	P
26	bh 28	2·48	16·7	50	18	13	15	G	G	P	M	P	P
27	bd 28	1·80	21·0	55	29	45	—	G	B	G	—	P	—
28	bc 28	2·74	14·7	60	14	12	—	M	B	M	—	P	—
29	bde 283	1·85	20·5	50	32	65	162	M	B	M	B	P	G
30	bdf 244	1·62	21·4	90	75	207	148	V	G	V	G	G	G

TABLE XXIII.—(Continued.)

Paint No.	Pigment[1]	Sp. Gr. at 70° F.[a]	Volatile Thinner. %[3]	Drying Time. Min.[2]	Efflux Time.[4],[5] Sec. I.	D.	W.	Condition in Tin D.	W.	Remixing D.	W.	Application D.	W.
84	jr 13	1·50	28·7	...	80	68	—	G	—[16]	V	—	V	—
85	fg 3/11	1·74	25·8	...	145	194	—	G	—[16]	V	—	G	—
72A[14]	h10	2·06	19·1	...	—	—	—	...	—[16]	—	—	—	—
AF8/42	...	1·50	30·6	120[16]	47[16]	42	10	G	G	—	G	V	V
					Paints in 100% Phenolic-Resin Media.								
76/1P[17]	gu 41	1·28	32·4	...[18]	26	30	—	G	B	V	—	V	—
76/2P	gu 41	1·34	29·6	...	25	35	—	G	B	V	—	V	—
77/1P	ab 32	1·41	29·7	...	35	80	—	G	B	V	—	V	—
77/2P	ab 32	1·59	26·1	...	36	90	—	G	B	V	—	V	—
78/1P	dg 41	1·28	33·3	...	33	41	—	G	B	V	—	V	—
78/2P	dg 41	1·38	29·6	...	41	80	—	G	B	V	—	V	—
79/1P	dgj 415	1·25	32·4	...	35	35	29	V	V[13]	V	V	V	V
79/2P	dgj 415	1·29	31·4	...	27	32	26	G	G[9]	V	V	V	V
80/1P	d 10	1·27	31·6	...	24	22	25	G	G	V	V	V	V
80/2P	d 10	1·36	26·6	...	25	28	27	M	M	M	M	V	V
81/1Q	ab 32	1·44	26·1	...	28	27	—	G	B	V	—	V	—
81/2Q	ab 32	1·66	25·6	...	26	23	55	G	B	V	—	V	—
82/1Q	dgj 415	1·29	30·0	...	26	19	135	G	G	V	V	V	V
82/2Q	dgj 415	1·40	22·1	...	31	29	—	G	G	V	G	V	V
83/1R	ab 32	1·40	19·2	...	35	30	—	G	B	V	G	V	V
83/2P	d 10	1·37	26·7	...	27	32	27	G	G	G	G	V	V

[a] Determined in August, 1942.

[1] *See* Table I, for the key to the pigments.
[2] By weight. The specific gravity of the thinners varied from 0·829 to 0·857 for paints Nos. 1 to 75, 84, 85.
[3] By weight.
[4] No. 4 Ford cup at 70° F. First 50 c.c. from a full cup.
[5] I.—Initial. D.—After storage at Derby for 9 months. W.—After storage at Woolwich (120° F.) for 6 months, plus 3 months at Derby. A dash indicates that the paint could not be remixed after storage. V = very good; G = good; M = moderate; B = bad.
[6] These paints were thinned at Caernarvon; the figures for the specific gravity and volatile thinner (%) refer to the samples as used. The storage tests were made on the unthinned paints.
[7-12] Withdrawn from climatic test after the following periods: [7] 1¼ months; slight leak through cap. [8] 1½ months; tin badly "blown." [9] 2½ months; tin "blown." [10] 2¾ months; tin "blown." [11] 3¼ months; slight leak through cap. [12] 3¾ months; tin "blown."
[13] Tin slightly "blown," after 6 months' climatic test. [14] Paint No. 72 as thinned at Caernarvon for use over aluminium- or zinc-pigmented paints.
[15] On October 10, 1942. [16] No storage test under these conditions. [17] P, Q, R refer to the medium, *see* Appendix B.
[18] The drying times of paints Nos. 76 to 83 were not determined.

except where the paint was no longer usable, a practical brushing test was made to assess the ease of application. In respect of each of these properties the paint was classified as very good, good, moderate or bad. Finally the efflux time (Ford cup) was redetermined wherever possible.

APPENDIX D.—*Details of Painting the Specimens. Series* A. *Caernarvon.*

(1) The method of painting the specimens has been briefly described in Section A, sub-section 1(c). The problem here is how to compress the large amount of detailed observations involved in this part of the work so as to avoid unduly fatiguing the general reader whilst retaining the essential facts for the comparatively few who may wish to make a critical study of the results. On the whole, the authors think it will meet the case if they supplement the information given in Table V. with Tables XXIV. and XXV.

TABLE XXIV.—*Series* A. *Caernarvon. Details of Painting (Paints Nos. 1–3).*

Paint.		Speci-men No.[1]	Frame No.[2]	Interval between $AF3$ and Immersion.		Weight of Wet Paint. G.				Weight of Dry Paint. G.			
No.	Pig-ment.					$AC1$.	$AC2$.	$AF3$.	Total.	$AC1$.	$AC2$.	$AF3$.[3]	Total.
				Hr.	Min.								
1	a 10	332020	2g	5	10	53	32	14·5	99·5	42	28·5	9·5	80
		310520	36c	5	45	38·5	35	16·5	90	33	31	11	75
2	ab 64	332024	17b	4	55	34·5	29	15	78·5	27	22·5	10	59·5
		310524	40e	5	30	32·5	21·5	13·5	67·5	26·5	18·5	9	54
3	ab 37	331919	24h	4	50	49·5	33·5	15·5	98·5	39	27	10·5	76·5
		310419	34a	4	55	39·5	28·5	13·5	81·5	34·5	24·5	9	68

[1] Specimen 33.... as-rolled and weathered 3 months; specimens 31.... pickled and weathered 6 days.
[2] The letters refer to the positions of the specimens in the frames.
[3] Calculated from weight of wet paint.

Table XXIV. gives, by way of illustration, full details of the observations recorded for the first three paints. The dates and times of applying each coat are not stated here, but are available in the Sub-Committee's records, together with details of the temperature and atmospheric humidity at the time of painting.

In Table XXV. are summarised the detailed data indicated in Table XXIV. by giving for each paint:

(a) The spreading rate of the first anti-corrosive coat calculated from the observed weight of wet paint used and the known specific gravity of the paint. Since the total area of a $15 \times 10 \times \frac{1}{4}$-in. specimen is 312·5 sq. in. (2016 sq. cm.) :

$$R = D \times 10 \times 453·6 \times 312·5/144 \times 9g = 1,094\ D/g \quad . \quad . \quad (1)$$

Paint.		Specimen I.[1]		Specimen II.[1]	
No.	Pigment.	Spreading Rate of $A\bar{C}1$. Sq. yd. per gal.	Total Paint Film Thickness. Microns.	Spreading Rate of $A\bar{C}1$. Sq. yd. per gal.	Total Paint Film Thickness. Microns.
1	*a* 10	73	87	101	81
2	*ab* 64	89	71	93	61
3	*ab* 37	67	92	82	77
4	*af* 28	69	105	73	91
5	*ak* 28	56	134	61	125
6	*ah* 28	104	63	128	62
7	*ad* 28	71	118	89	105
8	*ap* 73	71	115	89	99
9	*ae* 73	80	104	86	87
10	*ac* 28	97	84	107	80
11	*abp* 643	73	109	93	101
12	*ahp* 283	102	80	139	63
13	*adp* 283	64	114	72	106
14	*acp* 283	98	88	112	82
15	*ace* 283	86	81	94	78
16	*abf* 238	74	105	74	101
17	*abd* 238	67	123	77	108
18	*abc* 238	97	92	104	87
19	*adk* 244	64	130	90	101
20	*ack* 244	76	99	91	93
21	*acd* 244	78	105	102	87
22	*adg* 181	63	114	81	98
23	*b* 10	88	79	113	65
24	*bf* 28	94	97	68	107
25	*bk* 28	61	118	73	108
26	*bh* 28	109	72	132	63
27	*bd* 28	67	121	93	100
28	*bc* 28	106	75	124	77
29	*bde* 283	83	114	109	101
30	*bdf* 244	79	104	81	95
31	*bcf* 244	86	88	88	84
32	*bcd* 244	90	99	93	96
33	*bj* 82	92	83	128	65
34	*fn* 82	63	111	83	94
35	*dn* 82	73	107	93	98
36	*cn* 82	83	97	107	77
37	*den* 832	89	104	100	94
38	*cen* 832	68	91	81	81
39	*fq* 82	74	100	93	88
40	*dq* 82	69	114	88	106
41	*cq* 82	77	106	110	90
42	*fs* 82	63	113	77	104
43	*ds* 82	68	121	101	92
44	*fj* 82	71	106	82	96
45	*jk* 28	58	126	72	111

TABLE XXV.—(*Continued.*)

| Paint. | | Specimen I.[1] | | Specimen II.[1] | |
No.	Pigment.	Spreading Rate of ACl. Sq. yd. per gal.	Total Paint Film Thickness. Microns.	Spreading Rate of ACl. Sq. yd. per gal.	Total Paint Film Thickness. Microns.
46	cj 82	92	84	127	70
47	cej 832	83	84	109	74
48	dgj 415	67	114	90	95
49	jmq 721	77	81	99	70
50	jm 82	99	77	122	65
51	dj 73	72	102	107	91
52	g 10	66	101	74	92
53	gh 28	91	87	117	75
54	dg 82	74	94	113	81
55	cg 82	89	89	109	77
56	egh 328	66	103	89	88
57	deg 832	68	123	76	107
58	ceg 832	77	95	102	79
59	gj 82	79	120	99	98
60	hm 82	88	72	117	62
61	dm 82	82	107	98	94
62	cm 82	84	84	121	68
63	ehm 382	84	75	109	68
64	dem 832	76	106	89	101
65	cem 832	81	79	103	68
66	c 10	87	78	123	71
67	f 10	63	125	67	107
68	fk 82	70	125	73	114
69	afk 282	66	119	80	102
70	fkn 822	77	103	88	97
71	d 10	79	109	109	90
72	h 10	91	76	140	60
73	t 10	80	96	96	76
74	fr 82	59	127	71	113
75	dr 82	67	123	88	109
84[2]	jr 13	69	129	73	110
85[2]	jq 3/11	62	114	78	105
Paints in 100% Phenolic-Resin Media.					
76	qu 41/P	67	98	73	98
77	ab 32/P	63	96	86	87
78	qd 14/P	80	90	100	72
79	jgd 514/P	80	92	109	74
80	d 10/P	82	90	127	69
81	ab 32/Q	69	91	86	81
82	jgd 514/Q	81	102	129	79
83	ab 32/R; d/P	69	110	92	95

[1] I. = as-rolled and weathered for 3 months; II. = pickled and weathered for 6 days.

[2] *See* Table VII., footnote 3.

where D is the specific gravity of the wet paint, g the weight in grammes applied per specimen and R the spreading rate expressed in square yards per gallon.

The authors feel that this method of expressing the observations is more likely to be of value than a statement of the actual weight of paint applied per specimen, which has little meaning save to those thoroughly familiar with the experimental work.

(b) The calculated average total thickness of the dry paint film in microns (thousandths of a millimetre). This is taken as equal to the sum of the thicknesses of the three individual coats. The thickness of each coat has been calculated from the observed weights of wet paint by means of the equation :

$$t = 4 \cdot 96g \, (1 - Dv/d)/D \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where g is the weight of wet paint applied in grammes, D and d are the specific gravities of the mixed paint and volatile thinners, respectively, $100v$ is the percentage by weight of volatile thinners in the mixed paint, and t is the film thickness expressed in microns.

Values for the total film thickness calculated by equation (2) are approximate but they are roughly comparable for different paints.

(2) It will be noted from Table XXV. that there are fairly large variations in the spreading rate and also in the total film thickness from one paint to another. Such variations are to a great extent characteristic of the " build up " of each paint and the authors consider that more harm than good would be done by attempting to control them to a greater extent than has been done here ; they prefer that the paints should be applied naturally. Since the performance of a given paint will be influenced to some extent by the film thickness at which it is tested, it is desirable to show that the results observed in this investigation are not solely occasioned by this variable, i.e., that there is a genuine pigment effect, as distinct from any differences that might be attributed to differences in film thickness from one paint to another. This can be demonstrated as follows :

In Table XXVI. are shown the results of an analysis in which the 85 paints have been divided into eight groups of approximately ten paints each in order of decreasing merit figure. The average film thickness for the paints in each group is correlated with their average merit figure. It will be seen that, as one descends the scale from the best paints to the worst, there is no systematic decrease in the average film thickness. In fact, the thickness is practically constant for each group, and it may be concluded that in the majority of cases the variations in film thickness recorded have had no appreciable effect on the results.

(3) It may also be observed that, with few exceptions, the total

TABLE XXVI.—*Series* A. *Caernarvon. Correlation of Merit Figure with Film Thickness.*

Merit Figure.	Number of Paints in Group.	Average Film Thickness. Microns.	Average Merit Figure.
21–17	11	92	18·0
16–13	11	94	14·3
12–11	10	96	11·3
10–9	14	94	9·5
8–7	10	96	7·5
6–5	10	93	5·2
4–3	10	103	3·5
2–0	9	90	1·3

film thickness of a given painting scheme is greater on the as-rolled and weathered specimen than on the corresponding pickled and weathered one. This is largely due to the lower spreading rate of the first anti-corrosive coat on the former surface, which was more heavily rusted.

APPENDIX E.—*Experimental Results. Series* A. *Caernarvon.*

(1) *Introduction.*

Before presenting the experimental results in some detail, it is desirable to make a few comments on certain difficulties relating to the different methods of estimating paint breakdown.

(a) *Edge Effect.*—Failure of the paint film is particularly liable to occur first at the edges; this is partly due to the fact that the specimens are sheared from plate and, although the burr is removed by grinding and/or filing, the edges and corners remain relatively sharp. The authors have tried in earlier experiments to overcome this difficulty by giving an additional protective coat of paint to a narrow border round the edges, but experience has led them to prefer the expedient of ignoring the edges when inspecting the specimens and basing the results on the condition of the central 100 sq. in. of the paint film.

In the case of the best paints, such as Nos. 58 or 85 (Table VII.), the paint film remained intact right up to and on the edges throughout the whole duration of the tests.

(b) *Index Figure.*—Inspections at the exposure station are made in a standard manner and records taken of the fouling and corrosion of each specimen.[1] Since the present investigation is primarily concerned with anti-corrosive compositions, it is unnecessary to enlarge on the fouling aspect of the records save to remark that the fouling

[1] For details of the procedure followed *see* First Report of the Marine Corrosion Sub-Committee, *Journal of The Iron and Steel Institute*, 1943, No. I., p. 356 P.

that did occur rendered it more difficult to assess the condition of the paint film *in situ*.   As regards breakdown of the protective properties, observations are taken of chalking, cracking, blistering, flaking and rusting.   The last three variables are returned as the percentage of the total area affected by each ; the first two are assessed on a numerical scale only and are disregarded when calculating the so-called " index figure."   This has arbitrarily been taken throughout the present experimental series as the percentage blistering plus twice the percentage flaking plus four times the percentage rusting, the figures for both front and back faces being added together. Since the standard of failure laid down by the Sub-Committee corresponds approximately to 10% of rusting, the equivalent index figure for failure (sum of both faces) would be 80, and this figure has been adopted.

In these periodical inspections, carried out at sea, sometimes under adverse weather conditions, there is inevitably a fairly high personal error, *i.e.*, deviation in the assessments from one inspection to another.   In order to eliminate this, cumulative index figures have been calculated for this series of tests by taking the sum of the index figures at all the six inspections up to and including the last. The equivalent index figure for failure (*i.e.*, the moderate/bad boundary) has been calculated on the assumption that deterioration was directly proportional to time, so that the cumulative index figure corresponding to a final index figure of 80 at the last inspection after 36 weeks would be :

$$IF_{M/B} = 80(7 + 13 + 19 + 24 + 30 + 36)/36 = 287,$$

inspections having been made after 7, 13, &c., weeks, respectively.[1]

It is readily admitted that this method of treatment has its drawbacks.   For instance, certain types of zinc dust paint (not included in the present tests) blister extensively and show a proportionately high index figure, whereas in fact their anti-corrosive properties are excellent.   On the other hand, some such method is essential for the presentation and ready comprehension of the results, and it is certain that no paint with a low index figure can be other than a good one.

(c) *Rusting and Intact Paint*.—Both these variables are determined on the specimens after cleaning in running water on return to the laboratory.   It will be recalled that separate estimates are made for six subdivisions of the central area of 100 sq. in. on each face ; the method is illustrated by the typical set of results shown in Table XXVII.

In cases where the paint film has not flaked off and exposed the bare steel, it may be difficult to assess the percentage of rusting accurately, particularly when it is of the pin-head type and accom-

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[1] By simple proportion the index figure after 7 weeks of a specimen with an index figure of 80 after 36 weeks would be $80 \times \frac{7}{36}$, that after 13 weeks $80 \times \frac{13}{36}$, and so on.

TABLE XXVII.—*Typical Results of Final Laboratory Inspection.*[1]

Paint No. 67.

Specimen No.	Front.					Back.				
	A.	*B.*	*C.*	*D.*	*E.*	*A.*	*B.*	*C.*	*D.*	*E.*
I. As-rolled, weathered 3 months.[2]	30	10	0	60	...	40	30	0	30	...
	40	10	0	50	...	60	20	0	20	...
	30	20	2	48	...	30	20	0	50	...
	5	40	1	54	...	30	20	0	50	...
	10	50	0	40	...	20	50	0	30	...
	5	50	0	45	...	10	50	0	40	...
Mean	20	30	1	49	...	32	32	0	36	...
II. Pickled, weathered 6 days.	30	40	10	20	...	50	30	10	10	...
	40	20	10	30	100 *m*	70	5	5	20	...
	20	55	20	5	...	30	45	20	5	...
	20	57	20	3	...	30	63	5	2	...
	5	85	5	5	...	5	60	20	15	...
	5	80	5	10	...	5	55	10	30	...
Mean	20	56	12	12	...	32	43	12	13	...

[1] *A.*—Whole paint film intact, % by area.
B.—Anti-corrosive coat(s) intact only, % by area.
C.—Steel bare but unrusted, % by area.
D.—Steel rusted, % by area.
E.—Pit depths, mils (0·001 in.). *See also* footnote to Section A, subsection 1(*f*).

[2] Medium-sized blisters general and about 50 barnacle seatings on both faces.

panied by blistering. Moreover, the cleaning process may remove paint that would have remained adherent had immersion of the specimens been continued. It is clear, however, that a high figure for the percentage adhesion after cleaning indicates a good paint, whilst, as regards the assessment of rusting, it is a fact that, despite the difficulty mentioned, there is a good correlation between this and the index figure based on inspections in the field.

(d) *Loss in Weight.*—In this investigation the loss in weight of the specimens on exposure has been taken as the difference between the weight of the painted specimen as exposed and its weight after exposure and cleaning in the laboratory, no attempt being made to remove the adherent paint film. Hence, up to the limit of the weight of the coating itself, the loss in weight may merely represent loss of paint; beyond this some corrosion of the metal itself must have occurred.[1] Appraisal of the results is complicated by two factors :

(i) Some specimens may suffer excessive corrosion at the edges.

[1] In most cases, however, corrosion will occur long before all the paint is removed. Further, for strict accuracy, variations in the total weight of the dry paint film from one specimen to another should be taken into consideration, but this is unnecessary for the present purpose.

TABLE XXVIII.—*Detailed Experimental Results. Series A. Caernarvon.*

No.	Pigment	Merit Figure	Index Figure I	Index Figure II	Rusting I	Rusting II	Intact Paint I	Intact Paint II	Pits I	Pits II	Loss in Weight I	Loss in Weight II	Total Weight of Paint Film I	Total Weight of Paint Film II
1	a 10	4	263	92	21	11	161	61	...	60 m	3	54	80	75
2	ab 64	12	210	135	15	2	179	191	...	...	1	18	59·5	54
3	ab 37	12	163	77	5	4	193	186	...	...	1	16	76·5	68
4	af 28	2	407	588	27	28	170	169	...	32 m	2	21	41·5	36
5	ak 28	16	55	256	3	8	197	189	...	52 m	6	12	53·5	51·5
6	ah 28	4	179	241	11	39	187	60	...	36 c	-2	43	51·5	48
7	ad 28	13	194	264	5	2	195	198	...	...	6	22	58·5	53
8	ap 73	11	39	164	3	4	196	133	...	...	1	45	92·5	80
9	ae 73	10	32	195	4	5	194	79	...	16 c	4	40	82·5	68·5
10	ac 28	13	300	24	7	3	192	187	...	...	0	10	64·5	60
11	abp 643	11	34	165	2	10	197	130	...	...	-4	38	84	86·5
12	ahp 283	9	489	83	2	8	196	150	...	40 m	6	29	53·5	43
13	adp 283	9	373	570	9	2	191	196	...	40 f	1	35	62·5	59
14	acp 283	17	145	21	3	3	196	190	...	...	0	5	59·5	54
15	ace 283	17	71	20	4	2	194	196	...	...	1	6	57	56
16	abf 238	7	453	429	15	11	185	187	...	64 m	0	10	44	44·5
17	abd 238	17	75	130	3	0	197	200	...	...	9	24	64	59
18	abc 238	18	131	3	8	1	195	196	8 m	...	-1	8	65	63
19	adk 244	3	12	455	26	24	174	64	...	...	0	42	59·5	49
20	ack 244	11	75	85	15	6	184	189	...	...	-1	7	49	47
21	acil 244	20	15	22	2	2	198	193	...	...	-3	12	58·5	49·5
22	adg 181	8	157	326	16	7	178	191	...	...	8	27	50·5	46
23	b 10	10	278	193	5	7	191	183	...	...	11	14	60·5	49·5
24	bf 28	5	254	1048	34	16	166	181	...	...	-4	14	40·5	40
25	bk 28	9	145	362	10	5	189	194	...	...	0	19	45	43
26	bh 28	5	263	205	15	19	183	163	...	20 m	6	30	46·5	42·5
27	bd 28	8	178	229	30	6	167	194	...	...	15	25	57·5	49·5
28	bc 28	14	130	24	9	7	185	184	...	...	4	6	52	55·5
29	bde 283	10	42	435	10	7	190	192	...	...	1	37	55·5	50
30	bdf 244	8	316	671	4	12	196	188	...	...	15	26	43·5	41·5

No.	Ref	1	2	3	4	5	6	7	8	9	10	11	12	13
31	bef 244	41·5	41·5	15	7			164	179	31	19	379	448	3
32	bcd 244	54·5	58	14	−3			194	195	4	3	45	17	17
33	bj 82	44	55	41	21	48 c	12 f	44	193	19	7	166	149	7
34	fn 82	36	39·5	6	−6			162	182	31	18	765	389	4
35	din 82	49	51	39	22			190	178	4	12	333	486	5
36	cn 82	52	61·5	16	−1			146	193	14	5	49	234	10
37	dem 832	49	51	35	9			182	190	13	10	245	156	7
38	cen 832	58	63	10	2			186	190	5	9	23	46	15
39	fq 82	33	38·5	8	−1			178	181	22	19	465	466	5
40	dq 82	53	53	40	6			152	197	36	2	313	21	9
41	cq 82	57·5	67	16	2			180	196	9	4	28	12	15
42	fs 82	35·5	41	22	−1			175	163	3	37	421	334	3
43	ds 82	44	56	23	10			194	185	5	13	178	105	11
44	fy 82	38	36·5	28	2			150	176	14	24	264	504	2
45	jk 82	43	46	74	7	24 m		62	177	122	10	761	74	3
46	cj 82	45	55	18	6			170	182	8	6	29	196	10
47	cej 832	48·5	51	9	1			173	192	10	0	93	97	11
48	dgj 415	44	49·5	57	3	28 m		29	193	0	4	224	52	9
49	fmq 721	39	42·5	109	16		36 m	19	158	2	27	1440	327	0
50	jm 82	37·5	40·5	94	21		40 m	17	134	79	14	1251	239	2
51	dj 73	47	48	49	20			170	197	17	2	472	111	10
52	g 10°	35·5	40·5	16	4			181	188	10	12	263	99	9
53	gh 28°	41·5	44	30	16	26 m		178	164	16	24	150	230	5
54	dy 82°	39·5	42	44	4	12 c		74	195	102	5	602	112	6
55	cg 82°	41	46	3	−3	24 c		191	194	4	5	28	71	17
56	egh 328	39	45·5	33	10	8 m, c		115	159	79	41	384	178	1
57	deg 832	51·5	54·5	46	18	4 c		121	190	69	9	601	277	4
58	ceg 832°	45	50·5	2	2			194	197	4	2	13	43	20
59	gj 82	34·5	43	6	−4	12 c		174	195	4	3	156	84	13
60	hm 82	43·5	48	116	19	16 c		13	179	87	14	894	403	1
61	dim 82	47·5	52	39	29			186	190	−4	7	283	229	9
62	cm 82°	45·5	55·5	10	0			192	190	2	6	3	198	15
63	ehm 382	44·5	48·5	96	3			24	195	108	4	1236	48	7
64	dem 832	52·5	51·5	34	20			193	197	5	3	156	48	15
65	cem 832	46·5	52·5	2	1			195	192	3	6	4	88	17
66	c 10	50·5	57	13	1	40 m		159	190	10	7	75	279	10
67	f 10	39·5	42	21	3			151	114	25	85	745	347	1
68	fk 82	42·5	43·5	7	6			162	181	34	18	471	198	5
69	afk 289	41·5	43·5	11	2			175	170	24	30	499	279	4
70	fkm 822	37	36·5	11	5			172	193	26	6	493	173	8

TABLE XXVIII.—(Continued.)

No.	Pigment [2]	Merit Figure [3]	Index Figure [4] I.	Index Figure [4] II.	Rusting [5] I.	Rusting [5] II.	Intact Paint [5] I.	Intact Paint [5] II.	Pits [6] I.	Pits [6] II.	Loss in Weight [7] I.	Loss in Weight [7] II.	Total Weight of Paint Film [7] I.	Total Weight of Paint Film [7] II.
71	d 10	6	436	385	10	7	187	182	…	14½ m	29	42	51	45
72	h 10	2	82	879	34	38	165	97	…	12 c	0	70	47.5	41
73	t 10	3	84	536	17	53	183	147	…	…	-1	31	47	40.5
74	fr 82	1	397	417	40	18	158	125	…	…	-7	34	45.5	41
75	dr 82	7	81	84	27	2	171	148	…	…	14	42	53.5	50.5
84	jr 13 [10]	11	68	160	2	9	195	124	…	…	0	17	50.5	48
85	jq 3/11 [10]	20	36	16	1	4	199	196	…	…	-4	-3	64	60

Paints in 100% Phenolic-Resin Media.

No.	Pigment [2]	Merit Figure [3]	Index Figure [4] I.	Index Figure [4] II.	Rusting [5] I.	Rusting [5] II.	Intact Paint [5] I.	Intact Paint [5] II.	Pits [6] I.	Pits [6] II.	Loss in Weight [7] I.	Loss in Weight [7] II.	Total Weight of Paint Film [7] I.	Total Weight of Paint Film [7] II.
76	gu 41/P	11	174	70	5	5	175	194	(48 c) [8]	…	14	14	35	38
77	ab 32/P	18	38	7	4	2	195	191	…	…	-3	10	39	40
78	gd 14/P	14	92	194	6	3	193	196	…	…	5	19	33.5	29
79	jgd 514/P	5	230	332	8	92	192	104	…	12 f	-5	20	29	27.5
80	d 10/P	8	126	201	6	16	189	150	…	…	8	22	27	35
81	ab 32/Q	14	138	33	5	4	193	171	…	…	-3	9	34.5	36
82	jgd 514/Q	5	185	83	12	11	183	85	…	…	5	32	32.5	30.5
83	ab 32/R; d/P	12	103	55	9	3	180	163	…	…	5	15	37.5	32

[1] I.—As-rolled specimen weathered 3 months.   II.—Pickled specimen weathered 6 days.   See Table VI. for a statement of the significance of the various figures.

[2] The key to the pigments will be found in Table I.

[3] The merit figure is a general indication of the performance of the paint. It varies from a maximum possible value of 21 for the best paint downwards. For details of its calculation see Table VII.

[4] The best paints have the lowest index figures.

[5] Parts per 200, i.e., sum of the percentage returns for the front and back surfaces.

[6] In mils (0·001 in.); f, fine, diameter <2 mm.; m, medium 2-10 mm.; c, coarse >10 mm.

[7] Grammes per specimen.

[8] This pit is probably due to mechanical damage.

[9] See Table VII., footnote 2.

[10] See Table VII., footnote 3.

On this point the authors can only remark that a low loss in weight will indicate a good paint, even though the converse is not necessarily true.

(ii) There is a systematic difference in the behaviour of the specimens painted over the as-rolled surface weathered for 3 months and those painted over the pickled surface weathered for 6 days. This is evident from the curves shown in Fig. 4, which represent the
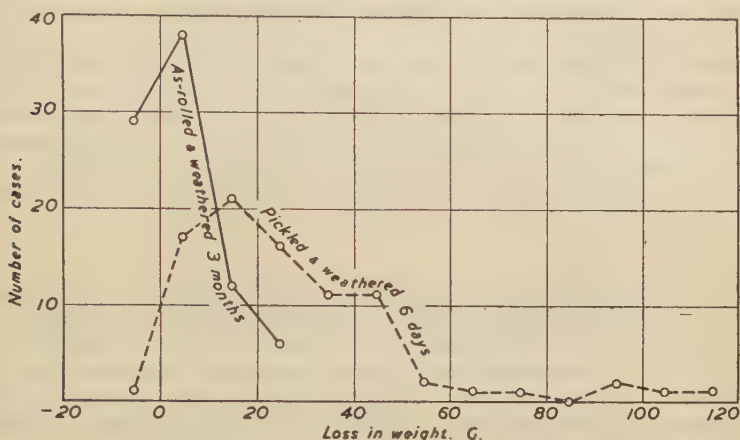
FIG. 4.—Losses in Weight on Exposure.   Series *A*.   Caernarvon.

frequencies of various ranges of loss in weight for the two types of surface.   Whereas, with one exception, all the pickled and weathered specimens show positive losses which are distributed over a wide range, 29 of the 85 as-rolled and weathered specimens show a negative loss (*i.e.*, gain in weight) and the range covered by the observations is much narrower.   The reason for this difference in behaviour is being explored.   Meanwhile it is clear that no marked distinction can be made between the losses in weight of the specimens painted over the as-rolled surface after weathering for 3 months.

It may assist the reader to appreciate the significance of the losses in weight recorded for the pickled specimens weathered for 6 days before painting if it is added that in earlier tests by the Sub-Committee at Plymouth on 35 three-coat proprietary painting schemes, many of which were of Admiralty quality, an average loss of 44·4 g. per specimen was observed after 29 weeks' immersion; in similar tests at Caernarvon on 42 painting schemes the corresponding figure was 53·9 g. after 26 weeks.[1]   In the present series the average loss in weight of the 85 specimens after 36 weeks was 27·4 g.   It would seem, therefore, that the formulated anti-corrosive paints tested at Caernarvon do not compare unfavourably with the

[1] First Report of the Marine Corrosion Sub-Committee, *loc. cit.*, p. 373 P. *See also* first footnote to Section A, sub-section 1(*b*)(i).

general run of proprietary anti-corrosive compositions, although some allowance should be made for the fact that the anti-fouling paint, $AF8/42$, used on the former may have exercised an additional protective effect.

(e) *General Conclusions.*—It is evident from the above that no one of the several variables that have been used here as a criterion of paint performance can be regarded as infallible in the negative sense, *i.e.*, it is possible that in some isolated cases a paint may have been unjustly condemned as bad.   On the other hand, it is equally certain that those paints that have come successfully through all the tests indicated are to be regarded as the best members of the series.   Since the immediate purpose is to establish formulations for satisfactory anti-corrosive compositions, this is to be regarded as sufficient for the time being.   Clearly, too, no great significance can be attached to minor differences in merit figures, &c., between individual paints.

(2) *Results.*

With these introductory remarks the complete experimental results may be presented.   They are shown in Table XXVIII.

It will be seen that there is a distinct difference in the performance of the paints on the as-rolled specimens weathered for 3 months before painting and on the pickled specimens weathered for 6 days only.   Paint adhesion is better on the former, whilst pitting is more prevalent on the latter; as regards pitting it should, however, be remembered that the as-rolled specimens had shed 92% of their scale, on the average, before being painted.   Discussion of these differences will best be postponed until the results of further experimental work by the Marine Corrosion Sub-Committee on the effects of surface condition are available.

APPENDIX F.—*Details of the Preparation and Compositions of Paints Nos. 86 to 148.*

The formulation and method of manufacture of the different media are described below ; the compositions of paints No. 86–148 are listed in Table XXIX :

Formulation and Method of Manufacture of the Different Media.

Unless otherwise stated, the compositions are given in parts by weight.

Synthetic-Resin Media.

Medium No. 2.   Modified Phenol-Formaldehyde/Stand-Oil.

Bedesol 66	64
Medium stand oil	128
White spirit	124
Lead-cobalt-manganese drier . .	$3\frac{1}{2}$

Method.—Heat stand oil to 220° C.   Add resin and heat to 240° C. until clear ($\frac{1}{2}$ hr. approx.).   Cool to 180° C., add thinner and driers.

Medium No. 5.   Modified Cresol-Formaldehyde/Stand-Oil.

Crestanol S.B.282	.	.	.	.	64
Medium stand oil	.	.	.	.	128
White spirit	.	.	.	.	124
Lead-cobalt-manganese drier	.	.	.	$3\frac{1}{2}$

Method.—As for medium No. 2.

Medium No. 8.   Alkyd + Zinc Resinate.

Paralac 15	.	.	.	.	200
Xylol	.	.	.	.	40
White spirit	.	.	.	.	40
Zinc-cobalt drier	.	.	.	.	11
Zinc resinate, 60%, in white spirit	.	25

Method.—Warm resin in white spirit until dissolved. Add driers and zinc resinate solution.

Medium No. 19.   British-Coumarone-A/Litho-Varnish.

Epok coumarone C.46 *	.	.	.	80
Litho varnish	.	.	.	.	80
White spirit	.	.	.	.	100
Lead-manganese drier	.	.	.	1

* Softening point (ball and ring) 102–107° C.

Method.—Heat resin and oil to 180° C. Thin and add driers.

Medium No. 21.   British-Coumarone-B/Litho-Varnish.

Coumarone resin *	.	.	.	.	80
Litho varnish	.	.	.	.	80
White spirit	.	.	.	.	100
Lead-manganese drier	.	.	.	1

* Softening point (ball and ring) 116° C. Sample supplied by Messrs. Dorman Long & Co., Ltd.

Method.—As for medium No. 19.

Medium No. 17.   U.S.A.-Coumarone-C/Litho-Varnish.

Coumarone resin *	.	.	.	.	80
Litho varnish	.	.	.	.	80
White spirit	.	.	.	.	100
Lead-manganese drier	.	.	.	1

* Softening point (ball and ring) 135–140° C. Sample supplied by Messrs. M. E. Dougherty, Ltd., on behalf of The Barrett Division of the Allied Chemical & Dyes Corporation, U.S.A.

Method.—As for medium No. 19.

Oleo-Resin Varnish Media.

Medium No. 6.   Refined-Linseed-Oil/Lime-Hardened-Rosin.

Rosin	.	.	.	.	.	.	51
Lime	.	.	.	.	.	.	3
Refined linseed oil	.	.	.	.	90
Naphtha	.	.	.	.	.	136
Lead-cobalt-manganese drier	.	.	2

Method.—Heat rosin to 240° C. Add lime ground in linseed oil. Keep at 240° C. until reaction subsides, add oil. Thin and add driers.

Medium No. 14.   Litho-Varnish/Lime-Hardened-Rosin.

Rosin	45
Lime	2½
Litho varnish	135
Naphtha	172
Lead-cobalt-manganese drier	25

Method.—As for medium No. 6.

Medium No. 20.   Litho-Varnish/Congo-Ester.

Litho varnish	90
Congo ester	30
Naphtha	66
White spirit	57
Lead-cobalt-manganese drier	9

Method.—20 parts of the oil and all the resin are heated together to 260° C. When clear the remaining oil is added gradually, keeping at 260° C. Heating time approx. 1½ hr. Cool to 180° C., add thinner, then driers.

Medium No. 4.   Litho-Varnish/Congo-Ester + Paraffin Wax.

Litho varnish	90
Congo ester	30
Naphtha	66
White spirit	57
Lead-cobalt-manganese drier	12
Paraffin wax	5

Method.—As for medium No. 20, the wax being added with the thinner.

Medium No. 11.   Litho-Varnish/Congo-Ester + Zinc Resinate.

Litho varnish	90
Congo ester	30
Naphtha	66
White spirit	49
Lead-cobalt-manganese drier	11
Zinc resinate, 60%, in white spirit	21

Method.—As for medium No. 20, the zinc resinate solution being added with the thinner.

Medium No. 12.   Tung-Oil/Lime-Hardened-Rosin.

Rosin	56
Raw tung oil	100
Lime	1½
Litharge	½
White spirit	116
Lead-cobalt drier	6½

Method.—Heat rosin and oil to 300° C., allow to cool. Add litharge at 260° C. and lime at 240° C. Thin at 180° C. and add drier.

Bituminous Media.

Medium No. 10.   Blown Bitumen.

Blown bitumen	120
Medium stand oil	67
White spirit	248
Lead-manganese drier	1

Method.—Heat together at 240° C. until dissolved. Allow to cool to 180° C., add thinner and then drier.

Medium No. 18.   *Bitumen.*

Gilsonite	180
Medium stand oil	67
White spirit	248
Lead-manganese drier	1

Method.—As for medium No. 10.

Medium No. 3.   *Bitumen + Ozokerite.*

Gilsonite	180
Medium stand oil	67
White spirit	248
Lead-manganese drier	1
Ozokerite	9

Method.—As for medium No. 10, the wax being added with the thinner.

Medium No. 7.   *Bitumen + Beeswax.*

Gilsonite	180
Medium stand oil	67
White spirit	248
Lead-manganese drier	1
Beeswax	9

Method.—As for medium No. 3.

Medium No. 13.   *Bitumen + Paraffin Wax.*

Gilsonite	180
Medium stand oil	67
White spirit	248
Lead-manganese drier	1
Paraffin wax	9

Method.—As for medium No. 3.

Sundry Media.

Medium No. 1.   *Aromatic Petroleum Residue.*

Firnigral	96
Rosin	32
Lime	$3\frac{1}{2}$
Boiled linseed oil	128
Lead-cobalt drier	43

Method.—Heat rosin and Firnigral to 180° C., add lime ground in oil and keep at 180° C. until reaction subsides.   Add oil, then driers.

Medium No. 9.   *Chlorinated Rubber.*

Chlorinated rubber	60
Cereclor	60
Xylol	180
Amyl acetate	20

Method.—Dissolve chlorinated rubber in amyl acetate and xylol in the cold; mix in Cereclor.

Medium No. 15.   *Shellac.*

1 gal. of 3-lb. shellac solution in 64 O.P. spirit.
1 gal. of 3-lb. manila solution in 64 O.P. spirit.
$\frac{1}{10}$ gal. of pine oil.

Method.—Mix cold.

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TABLE XXIX.—*Compositions of Paints Nos. 86–148.*

The compositions are stated throughout as percentages by weight.   The Ford cup efflux time is that required for the first 50 c.c. of paint to flow from a full No. 4 Ford cup at 70° F.

Medium.	Pigmentation Code.[1]		
	d.	*de* 64.	*den* 642.
1. *Aromatic Petroleum Residue*	*86.*	*87.*	*88.*
Pigment	66·8	67·6	67·0
Non-volatile vehicle . . .	27·3	26·0	26·5
Thinner, sp. gr. 0·880 . . .	5·9	6·4	6·5
Weight per gal. Lb. . . .	19·8	20·0	20·0
Ford cup efflux time. Sec. . .	47	28	34
2. *Modified Phenol-Formaldehyde/Stand-Oil.*	*89.*	*90.*	*91.*
Pigment	64·0	65·4	64·8
Non-volatile vehicle . . .	19·9	19·0	20·0
Thinner, sp. gr. 0·820 . . .	16·1	15·6	15·2
Weight per gal. Lb. . . .	18·8	19·0	19·0
Ford cup efflux time. Sec. . .	57	46	68
3. *Bitumen + Ozokerite.*	*92.*	*93.*	*94.*
Pigment	65·3	67·0	65·2
Non-volatile vehicle . . .	15·2	14·6	14·9
Thinner, sp. gr. 0·800 . . .	19·5	18·4	18·9
Weight per gal. Lb. . . .	18·0	18·2	18·0
Ford cup efflux time. Sec. . .	129	112	136
4. *Litho-Varnish/Congo-Ester + Paraffin Wax.*	*95.*	*96.*	*97.*
Pigment	62·7	64·2	63·6
Non-volatile vehicle . . .	19·2	18·5	19·2
Thinner, sp. gr. 0·840 . . .	17·1	17·3	17·2
Weight per gal. Lb. . . .	17·8	18·4	18·2
Ford cup efflux time. Sec. . .	66	60	71
5. *Modified Cresol-Formaldehyde/Stand-Oil*	*98.*	*99.*	*100.*
Pigment	63·3	64·7	63·5
Non-volatile vehicle . . .	19·7	18·8	19·5
Thinner, sp. gr. 0·820 . . .	17·0	16·5	17·0
Weight per gal. Lb. . . .	18·4	18·8	18·8
Ford cup efflux time. Sec. . .	175	125	136
6. *Refined-Linseed-Oil/Lime-Hardened-Rosin.*	*101.*	*102.*	*103.*
Pigment	68·6	69·8	68·8
Non-volatile vehicle . . .	17·1	16·4	16·9
Thinner, sp. gr. 0·880 . . .	14·3	13·8	14·3
Weight per gal. Lb. . . .	19·8	20·2	20·0
Ford cup efflux time. Sec. . .	13	8	9

TABLE XXIX.—(*Continued.*)

Medium.	Pigmentation Code.[1]		
	d.	*de* 64.	*den* 642.
7. *Bitumen + Beeswax.*	104.	105.	106.
Pigment	64·7	66·2	64·8
Non-volatile vehicle . . .	15·0	14·4	14·9
Thinner, sp. gr. 0·800 . .	20·3	19·4	20·3
Weight per gal. Lb. . .	18·0	18·8	18·4
Ford cup efflux time. Sec. .	105	117	74
8. *Alkyd + Zinc Resinate.*	107.	108.	109.
Pigment	64·5	67·2	67·2
Non-volatile vehicle . . .	19·2	18·1	19·8
Thinner, sp. gr. 0·840 . .	16·3	14·7	13·0
Weight per gal. Lb. . .	18·4	19·8	20·0
Ford cup efflux time. Sec. .	38	50	107
9. *Chlorinated-Rubber.*	110.	111.	112.
Pigment	58·6	60·6	58·0
Non-volatile vehicle . . .	13·0	12·6	12·6
Thinner, sp. gr. 0·870 . .	28·4	26·8	29·4
Weight per gal. Lb. . .	18·0	18·4	18·2
Ford cup efflux time. Sec. .	30	33	27
10. *Blown-Bitumen.*	113.	114.	115.
Pigment	64·9	66·3	65·2
Non-volatile vehicle . . .	15·0	14·4	14·9
Thinner, sp. gr. 0·800 . .	20·1	19·3	19·9
Weight per gal. Lb. . .	18·6	18·6	18·2
Ford cup efflux time. Sec. .	73	48	46
11. *Litho-Varnish/Congo-Ester + Zinc*			
Resinate.	116.	117.	118.
Pigment	62·5	63·7	64·2
Non-volatile vehicle . . .	18·6	17·7	18·8
Thinner, sp. gr. 0·840 . .	18·9	18·6	17·0
Weight per gal. Lb. . .	18·2	18·4	18·6
Ford cup efflux time. Sec. .	72	48	92
12. *Tung-Oil/Lime-Hardened-Rosin.*	119.	120.	121.
Pigment	67·8	69·4	68·0
Non-volatile vehicle . . .	20·2	19·2	20·1
Thinner, sp. gr. 0·800 . .	12·0	11·4	11·9
Weight per gal. Lb. . .	19·4	19·4	19·4
Ford cup efflux time. Sec. .	30	25	26
13. *Bitumen + Paraffin Wax.*	122.	123.	124.
Pigment	65·4	66·9	65·1
Non-volatile vehicle . . .	15·2	14·6	14·9
Thinner, sp. gr. 0·800 . .	19·4	18·5	20·0
Weight per gal. Lb. . .	17·6	18·2	18·0
Ford cup efflux time. Sec. .	73	75	106

TABLE XXIX.—(*Continued.*)

Medium.	Pigmentation Code.[1]		
	d.	*de* 64.	*den* 642.
14. *Litho-Varnish/Lime-Hardened-Rosin.*	*125.*	*126.*	*127.*
Pigment	58·5	62·1	61·0
Non-volatile vehicle . . .	17·6	17·3	18·0
Thinner, sp. gr. 0·880 . . .	23·9	20·6	21·0
Weight per gal. Lb. . . .	17·2	18·0	17·8
Ford cup efflux time. Sec. . .	118	130	118
15. *Shellac.*	*128.*	*129.*	*130.*
Pigment	62·4	64·1	64·0
Non-volatile vehicle . . .	7·8	7·4	7·7
Thinner, sp. gr. 0·830 . . .	29·8	28·5	28·3
Weight per gal. Lb. . . .	18·0	18·4	18·2
Ford cup efflux time. Sec. .	15	10	9
16. *Lanolin.*	*131.*	*132.*	*133.*
Pigment	62·8	64·5	63·2
Non-volatile vehicle . . .	26·2	25·0	25·7
Thinner, sp. gr. 0·880 . . .	11·0	10·5	11·1
Weight per gal. Lb. . . .	18·6	18·8	18·4
Ford cup efflux time. Sec. .	180	130	150
17. *U.S.A.-Coumarone-C/Litho Varnish.*	*134.*	*135.*	*136.*
Pigment	62·2	63·6	63·0
Non-volatile vehicle . . .	18·1	17·2	18·9
Thinner, sp. gr. 0·820 . . .	19·7	19·2	18·1
Weight per gal. Lb. . . .	18·0	18·2	18·0
Ford cup efflux time. Sec. .	51	38	62
18. *Bitumen.*	*137.*	*138.*	*139.*
Pigment	64·9	66·4	65·2
Non-volatile vehicle . . .	15·1	14·4	14·9
Thinner, sp. gr. 0·800 . . .	20·0	19·2	19·9
Weight per gal. Lb. . . .	17·6	18·2	18·0
Ford cup efflux time. Sec. .	46	48	42
19. *British-Coumarone A/Litho Varnish.*	*140.*	*141.*	*142.*
Pigment	62·2	63·6	63·0
Non-volatile vehicle . . .	18·1	17·2	18·9
Thinner, sp. gr. 0·820 . . .	19·7	19·2	18·1
Weight per gal. Lb. . . .	18·0	18·4	18·4
Ford cup efflux time. Sec. .	96	64	114
20. *Litho-Varnish/Congo-Ester.*	*143.*	*144.*	*145.*
Pigment	61·4	64·1	64·0
Non-volatile vehicle . . .	17·8	17·3	17·4
Thinner, sp. gr. 0·840 . . .	20·8	18·6	18·6
Weight per gal. Lb. . . .	17·6	18·2	18·0
Ford cup efflux time. Sec. .	41	43	44

TABLE XXIX.—(*Continued.*)

Medium.	Pigmentation Code.[1]		
	d.	*de* 64.	*den* 642.
21. *British-Coumarone*-B/*Litho Varnish.*	*146.*	*147.*	*148.*
Pigment	62·2	63·6	63·0
Non-volatile vehicle . . .	18·1	17·2	18·9
Thinner, sp. gr. 0·820 . . .	19·7	19·2	18·1
Weight per gal. Lb. . . .	17·8	18·2	18·2
Ford cup efflux time. Sec. . .	24	22	37

[1] *d* = Burntisland red; *de* 64 = Burntisland red and barytes; *den* 642 = Burntisland red, barytes and barium chromate.

Medium No. 16.—*Lanolin.*

Lanolin	100
Rosin	40
Lime	8
Boiled linseed oil	140
Naphtha	48
Lead-cobalt drier . . .	29

Method.—Heat lanoline and rosin to 180° C. Add lime ground in oil. Keep at 180° C. until reaction subsides. Add oil, thinner and drier.

APPENDIX G.—*Physical Properties and Results of Storage Tests. Paints Nos. 86 to 148 and* AF1/43.

Samples of the Emsworth series of paints, *viz.*, Nos. 86–148 and *AF*1/43, were subjected to storage tests as follows :

(*a*) Stored for 11 months at ordinary laboratory temperature (60–70° F.).

(*b*) Stored for 6 months under " tropical conditions " (120° F.) plus additional periods of storage at normal temperature at Derby, before and after this treatment, totalling 5 months in all.

Each sample was contained in a 1-pint size taper tin, closed with a metal plug and capped with a patent seal. An air space of approximately 50 c.c. was left over each paint.

At the conclusion of the test, each sample was examined systematically and the following properties were observed, wherever possible :

(1) *Skin formation.*
(2) *Separation of pigment*, leaving clear vehicle on top.
(3) *Settlement* :

    (*a*) As regards quantity.
    (*b*) As regards hardness, classified as follows :

TABLE XXX.—*Physical Properties and Results of Storage Tests.   Paints Nos. 86 to 148 and AFI/43.*

No.	Designation	Pigment [1]	Paint No.	Sp. Gr. at 70° F. L	Efflux Time [3,4] L	D	W	Condition in Container [3,4] D	W	Brushability [3,4] D	W	Drying Properties [3,4] D	W
	Synthetic-Resin Media.												
2	Modified phenol-formaldehyde/stand-oil.	d / de 64 / den 642	89 / 90 / 91	1·88 / 1·90 / 1·90	57 / 46 / 68	105 / 97 / 106	67 / 57 / -	M / M / V	M / M / B	F / F / S	S / S / -	H / H / H	H / H / -
5	Modified cresol-formaldehyde/stand-oil.	d / de 64 / den 642	98 / 99 / 100	1·84 / 1·88 / 1·88	175 / 125 / 136	302 / - / -	105 / 132 / 160	G / B / B	V / V / V	F / - / -	F / F / F	H / - / -	T / T / T
8	Alkyd + zinc resinate.	d / de 64 / den 642	107 / 108 / 109	1·84 / 1·98 / 2·00	38 / 50 / 107	46 / 44 / 112	27 / 24 / 56	G / M / G	G / G / G	G / S / F	G / S / S	S / S / S	S / S / S
19	British-coumarone-A/litho-varnish.	d / de 64 / den 642	140 / 141 / 142	1·80 / 1·84 / 1·84	96 / 64 / 114	106 / 79 / 158	33 / - / -	G / M / M	M / B / B	F / S / F	S / - / -	T / T / T	T / - / -
21	British-coumarone-B/litho-varnish.	d / de 64 / den 642	146 / 147 / 148	1·78 / 1·82 / 1·82	24 / 22 / 37	28 / 25 / -	- / - / -	G / M / B	B / B / B	E / E / -	- / - / -	S / S / -	T / - / -
17	U.S.A.-coumarone-C/litho-varnish.	d / de 64 / den 642	134 / 135 / 136	1·80 / 1·82 / 1·80	51 / 38 / 62	75 / 48 / 118	- / - / 45	G / G / V	B / B / M	S / S / F	- / - / G	H / H / H	- / - / H
	Oleo-Resin Varnish Media.												
6	Refined-linseed-oil/lime-hardened-rosin.	d / de 64 / den 642	101 / 102 / 103	1·98 / 2·02 / 2·00	13 / 8 / 9	19 / 13 / 11	12 / 10 / 10	P / P / P	V / B[5] / B[5]	G / G / G	G / E / E	S / S / S	S / S / S
14	Litho-varnish/lime-hardened-rosin.	d / de 64 / den 642	125 / 126 / 127	1·72 / 1·80 / 1·78	118 / 130 / 118	480 / 235 / Too thick.	24 / 30 / 45	G / G / M	P / P / P	F / F / F	S / G / G	H / H / S	H / S / S

Each material column carries three sub-values corresponding to the conditions **d / de 64 / den 642**.

No.	Material	Condition			Grades										Sp. gr.	Ser.
20	Litho-varnish/Congo-ester.	d	de 64	den 642	T T – / T T T / S S – / S S S / M M B / M M M							22 22 –	50 48 50	41 43 44	1·76 1·82 1·80	143 144 145
4	Litho-varnish/Congo-ester + paraffin wax.	d	de 64	den 642	T T – / S S – / S S – / S S – / G M B / G M B							39 37 –	78 100 –	60 60 71	1·78 1·84 1·82	95 96 97
11	Litho-varnish/Congo-ester + zinc resinate.	d	de 64	den 642	T T – / – T T / S S – / – S F / G M B / B G G							29 22 –	– 47 180	72 48 92	1·82 1·84 1·86	116 117 118
12	Tung-oil/lime-hardened-rosin.	d	de 64	den 642	S S H / H S H / S S F / G F S / V V V / V V V							90 94 72	90 350 51	30 25 26	1·94 1·94 1·94	119 120 121
Bituminous Media.																
10	Blown bitumen.	d	de 64	den 642	– – S / S S T / – – S / S S S / B B G / V V V							– – 74	181 93 85	73 48 46	1·86 1·86 1·82	113 114 115
18	Bitumen.	d	de 64	den 642	– – – / – – – / – – – / – – – / B B B / B B B							– – –	– – –	46 48 42	1·76 1·82 1·80	137 138 139
3	Bitumen + ozokerite.	d	de 64	den 642	– – – / – H – / – – – / – F – / B B B / B M B							– – –	– 150 –	129 112 136	1·80 1·82 1·80	92 93 94
7	Bitumen + beeswax.	d	de 64	den 642	– – – / H – – / – – – / S – – / B B B / M B B							– – –	146 – –	105 117 74	1·80 1·88 1·84	104 105 106
13	Bitumen + paraffin wax.	d	de 64	den 642	– – – / – – – / – – – / – – – / B B B / B B B							– – –	– – –	73 75 106	1·76 1·82 1·80	122 123 124
Sundry Media.																
1	Aromatic petroleum residue.	d	de 64	den 642	S S S / S S S / S S S / S S S / L L L / V V V							32 23 30	42 26 28	47 28 34	1·98 2·00 2·00	86 87 88
9	Chlorinated rubber	d	de 64	den 642	H H – / H H H / S S – / S S G / G M B / G G M							38 39 –	36 36 31	30 33 27	1·80 1·84 1·82	110 111 112

TABLE XXX.—(Continued.)

Medium		Pigment[1]	Paint No.	Sp. Gr. at 70° F. I.	Efflux Time[3,4]			Condition in Container[3,4]		Brushability[3,4]		Drying Properties[3,4]	
No.	Designation.				I.	D.	W.	D.	W.	D.	W.	D.	W.
Sundry Media (continued.)													
15	Shellac.	d de 64 den 642	128 129 130	1·80 1·84 1·82	15 10 9	10 9 10	15 11 —	P P P	P P B	S S S	S S —	H H H	H H —
16	Lanolin.	d de 64 den 642	131 132 133	1·86 1·88 1·84	180 130 150	{ Too thick	— — —	M M M	B B B	S F F	— — —	S S S	— — —
Anti-Fouling Composition.													
	Litho-varnish/Congo-ester-rosin.	de 64	AF1/43	1·98	93	67	69	P	B[5]	S	S	H	H

[1] d = Burntisland red; de 64´ = Burntisland red and barytes; den 642 = Burntisland red, barytes and barium chromate.
[3] In seconds for the first 50 c.c. from a full No. 4 Ford cup at 70° F. I.—Initial. D.—After storage at normal temperature for 11 months. W.—After storage at 120° F. for 6 months and at normal temperature for 5 months.
[3] See text for explanation of symbols.
[4] A dash indicates that the paint was unusable after storage.
[5] Tin "blown."

> V.—Soft; can be redispersed by hand-stirring in 2–3 min.
>
> G.—Fairly hard; can be redispersed in 4–10 min.
>
> M.—Hard; can be redispersed in 11–20 min.
>
> B.—Very hard; impossible to redisperse by hand-stirring within a reasonable time.

(4) *Thickening or Fattening.*

(5) *Thixotropy.*

(6) *Brushability*, assessed as follows :

> E.—Too thin; very easy to apply.
>
> G.—Good; little resistance to the brush; leaves good thick coat.
>
> S.—Satisfactory; may pull slightly and need a small addition of thinner.
>
> F.—Fair; pulls slightly and needs thinning.

(7) *Drying Properties.*—The condition of the film after drying overnight was observed. For simplicity of presentation, the observations are grouped here as follows :

> H.—Very hard, hard or medium hard.
>
> S.—Soft or very soft.
>
> T.—Slightly tacky, tacky, sticky or wet.

For practical purposes, the drying properties of paints classed in the first two categories may be considered reasonably satisfactory, but paints that are slightly tacky after 24 hr. are not easily overcoated and are regarded as unsatisfactory.

(8) *Efflux Time.*—Efflux time of the first 50 c.c. from a full No. 4 Ford cup at 70° F.

(9) *Gas Formation.*—Recorded as present when the container is " blown."

Results.—In view of the experimental nature of these paints it is unnecessary to give full details of the final examination, and their storage properties will be adequately covered by presenting the data recorded under four heads :

(a) *Condition in container*, assessed as V (very good), G (good), M (moderate), or B (bad), on the basis of properties (1), (3b), (4) and (9).

(b) *Brushability* (6).

(c) *Drying properties* (7).

(d) *Efflux time* (8).

A summary of the results on this basis will be found in Table XXX. together with particulars of the specific gravity of the paints taken shortly after their preparation.

It will be seen that in no case are the storage properties of any of the paints in the eight best media (*see* Table XIX.) entirely satis-

factory. The best medium in this respect is No. 8, alkyd plus zinc
resinate.

APPENDIX H.—*Details of Painting the Specimens. Series* B.
Emsworth.

(1) In Table XXXI. will be found details of the painting of the
Emsworth specimens expressed in the form already adopted in the
case of the specimens of series *A* at Caernarvon. If necessary,
Appendix D, relating to the latter series, should be consulted for
explanatory comments.

(2) It will be seen from Table XXXI. that at Emsworth, as at
Caernarvon, there were appreciable differences in the rates at which
the paints were applied, resulting from innate differences in their
characteristics ; moreover, the spreading rates of the anti-corrosive
were in general greater, *i.e.*, the films were thinner, than at Caernar-
von. The question again arises as to whether these differences in
spreading rate have had any significant effect on the results. In
this case the authors have investigated the matter by calculating
the correlation coefficient by Spearman's " ranking method " [1]
between the order of the media arranged according to their " merit
figure " (*see* Table XVIII.) and their order when arranged according
to the average film thickness of the paints prepared from them (*see*
Table XXXI.[2]). The resulting value is −0·024, showing the com-
plete absence of any such correlation for the family of paints as a
whole. The order of merit of the media under the given conditions
of test may, therefore, be accepted with confidence.

APPENDIX J.—*Experimental Results. Series* B. *Emsworth.*

Details of the individual results for the Emsworth specimens are
given in Table XXXII. as regards the following :

(a) *The Index Figure.*—This is the individual index figure, *i.e.*,
the percentage of blistering plus twice the percentage of flaking plus
four times the percentage of rusting, summed for both faces, as
determined at the last inspection after 24 weeks. Consequently,
a value of 80 would correspond to failure. It will be recalled that
when assessing the Caernarvon results (Appendix E) the cumulative
index figure (the sum for all inspections) was taken. The difference
in the method adopted would have little effect in the Emsworth
tests, since the Spearman correlation coefficient of the orders of
merit according to the individual or cumulative index figures at 24
weeks, respectively, is 0·969.

[1] Spearman's correlation coefficient, $\rho = 1 - 6\Sigma\Delta^2/(n^3 - n)$, where Δ
is the difference between the two ranking orders in any individual case and
n is the number of observations—in this case 21. (*See* J. L. Holman, " Simpli-
fied Statistics," p. 71. London, 1938 : Sir Isaac Pitman & Sons, Ltd.).
[2] The average total film thickness for all six specimens coated with paints
in the same medium irrespective of the pigmentation was used here.

TABLE XXXI.—*Spreading Rate of ACI and Total Paint Film Thickness. Series B. Emsworth.*

No.	Medium. Type.	Spreading Rate of ACI. Sq. yd. per gal.[1] — $d.$[2] 1.	$d.$[2] 2.	$de\ 64.$[2] 3.	$de\ 64.$[2] 4.	$den\ 642.$[2] 5.	$den\ 642.$[2] 6.	Total Paint Film Thickness. Microns.[1] — $d.$[2] 1.	$d.$[2] 2.	$de\ 64.$[2] 3.	$de\ 64.$[2] 4.	$den\ 642.$[2] 5.	$den\ 642.$[2] 6.
Synthetic-Resin Media.													
2	Modified phenol-formaldehyde/stand-oil.	149	96	117	102	100	100	121	122	106	119	119	125
5	Modified cresol-formaldehyde/stand-oil.	66	101	68	78	84	81	153	115	141	140	126	120
8	Alkyd + zinc resinate.	116	123	78	101	63	71	112	116	133	117	155	157
19	British-coumarone-A/litho-varnish.	1.3	168	164	179	92	99	97	90	103	94	114	115
21	British-coumarone-B/litho-varnish.	119	137	162	196	106	118	95	89	82	81	106	105
17	U.S.A.-coumarone-C/litho-varnish.	138	176	206	217	92	129	109	91	83	84	126	111
Oleo-Resin Varnish Media.													
6	Refined-linseed-oil/lime-hardened-rosin.	124	157	120	167	143	164	102	96	105	99	89	89
14	Litho-varnish/lime-hardened-rosin.	137	119	107	88	74	87	113	103	113	122	129	107
20	Litho-varnish/Congo-ester.	108	118	106	134	161	110	94	95	102	89	82	94
4	Litho-varnish/Congo-ester + paraffin wax.	93	116	99	104	93	109	115	110	110	110	124	112
11	Litho-varnish/Congo-ester + zinc resinate.	139	126	131	147	112	101	101	106	98	110	122	121
12	Tung-oil/lime-hardened-rosin.	127	107	122	110	134	101	122	110	117	122	106	110
Bituminous Media.													
10	Blown bitumen.	124	124	159	129	139	130	109	101	95	94	99	105
18	Bitumen.	134	154	186	260	176	241	102	89	93	83	91	84
3	Bitumen + ozokerite.[3]	104	110	100	106	63	113	117	115	125	117	143	120
7	Bitumen + beeswax.	104	101	84	91	123	136	118	112	126	116	108	109
13	Bitumen + paraffin wax.[3]	151	130	157	139	121	138	122	123	107	121	109	124
Sundry Media.													
1	Aromatic petroleum residue.	132	118	148	104	159	104	140	132	106	140	119	156
9	Chlorinated rubber.	94	101	90	97	134	122	102	110	107	100	88	90
15	Shellac.	110	133	152	152	114	118	75	63	75	67	72	75
16	Lanolin.	83	118	122	139	117	131	141	125	145	114	118	110

[1] When calculating these quantities the necessary slight alterations were made in the constants of equations (1) and (2) of Appendix D to correspond with the fact that the specimens were ¼ in. thick instead of ⅛ in.

[2] Pigments: d, Burntisland red; $de\ 64$, Burntisland red, barytes; $den\ 642$, Burntisland red, barytes, barium chromate.

[3] These paints were found to be very thick when applied.

TABLE XXXII.—*Detailed Experimental Results. Series B. Emsworth.*

No.	Medium. Description.	Merit Figure.	Index Figure, 24 Weeks. $d.^1$ 1.	2.	de 64.^{1} 3.	4.	den 642.^{1} 5.	6.	Mean.	Rusting, Parts per 200. $d.^1$ 1.	2.	de 64.^{1} 3.	4.	den 642.^{1} 5.	6.	Mean.	Loss in Weight. G.
	Synthetic-Resin Media.																
2	Modified phenol-formaldehyde/standard oil.	23	66	49	46	66	19	55	50	2	3	2	5	1	5	1·5	33
5	Modified cresol-formaldehyde/standard oil.	30	25	35	13	34	47	36	32	0	2	1	1	1	1	0·5	18
8	Alkyd + zinc resinate.	15	120	113	90	82	43	19	78	10	11	7	5	2	2	3·1	20
19	British-coumarone-A/litho-varnish.	26	56	76	41	45	35	31	48	1	3	3	1	1	1	0·8	18
21	British-coumarone-B/litho-varnish.	14	44	95	107	90	60	75	79	0	6	10	20	4	1	3·4	12
17	U.S.A.-coumarone-C/litho-varnish.	16	67	82	100	181	45	37	85	1	4	12	22	2	2	3·6	21
	Oleo-Resin Varnish Media.																
6	Refined-linseed-oil/lime-hardened-rosin.	1	300	400	280	460	372	368	363	28	16	20	41	24	41	14·2	27
14	Litho-varnish/lime-hardened-rosin.	3	280	327	290	165	120	361	257	40	89	14	18	13	29	16·9	33
20	Litho-varnish/Congo-ester.	4	75	110	185	185	163	94	135	19	12	44	26	23	14	11·5	11
4	Litho-varnish/Congo-ester + paraffin wax.	3	268	265	364	362	279	347	314	16	15	26	28	16	37	11·5	·36
11	Litho-varnish/Congo-ester + zinc resinate.	3	86	120	155	215	160	133	145	15	12	32	22	47	16	12·0	23
12	Tung-oil/lime-hardened-rosin.	11	68	106	102	106	53	225	110	7	5	24	9	4	14	5·3	11
	Bituminous Media.																
10	Blown bitumen.	10	182	218	248	250	310	308	253	7	8	7	10	9	11	4·3	9
18	Bitumen.	12	128	196	135	166	74	88	131	6	10	5	5	6	6	3·2	3
8	Bitumen + ozokerite.	11	100	122	112	178	68	144	121	9	7	6	18	4	10	4·5	9
7	Bitumen + beeswax.	13	122	157	67	93	102	89	105	5	7	4	8	6	5	2·9	9
13	Bitumen + paraffin wax.	0	432	449	393	508	445	492	453	84	97	56	153	111	99	50·0	54
	Sundry Media.																
1	Aromatic petroleum residue.	2	184	257	372	357	347	192	285	7	44	20	24	26	24	12·1	41
9	Chlorinated rubber.	23	125	103	64	28	33	16	62	5	4	1	2	2	2	1·3	—3
15	Shellac.	11	63	164	94	112	106	98	105	8	8	9	9	11	18	5·3	—3
16	Lanolin.	0	350	408	325	323	373	340	353	30	36	28	39	41	28	16·8	33

¹ Pigments: d = Burntisland red; de 64 = Burntisland red and barytes; den 642 = Burntisland red, barytes and barium chromate.

(b) *The Amount of Rusting.*—This is the value in parts per 200 (the sum of the percentages for both faces) determined for the cleaned specimens in the laboratory; as previously stated, a band about 1 in. wide round the edges is ignored when making the observations.

The correlation between the two sets of observations is good. The Spearman correlation coefficient for the order of merit according to the mean index figure and the order of merit according to the mean amount of rusting is 0·913.

(c) *The Loss in Weight.*—In addition, the value is given of the mean loss in weight of each set of six specimens coated with paints in the same medium. This is the difference between the weight of the fully painted specimen before exposure and its weight after cleaning (but without any deliberate stripping of the paint) on the conclusion of the test. The correlation between the order of merit based on the loss in weight and that based on the index figure is poor, the correlation coefficient being 0·472. This is probably due to the severe attack on the edges of many of the specimens, which led to marked stripping of the paint from the edges inwards. Consequently, the loss in weight of the specimens has not been taken into consideration when assessing the results.

CORRESPONDENCE.

Mr. C. M. JACKSON (Messrs. Devoe and Raynolds Co., Inc., Malden, Mass., U.S.A.) wrote : Included in the list of pigments tested are several which are not commonly used in the United States of America. These are Burntisland red, Bideford black, witherite and possibly barium chromate. An omission from the investigation was lead chromate, for which we have high regard as a corrosion-inhibiting pigment.

When formulating paints, particularly primers, the control of the pigment vehicle content is considered of fundamental importance ; this is usually referred to as the P.V.C. of a paint, and is figured as a percentage as follows :

$$\frac{\text{Volume of pigment in total paint solids}}{\text{Volume of pigment} + \text{Volume of non-volatile vehicle}} \times 100 = \text{P.V.C.}$$

No mention was made in the paper as to whether this figure was controlled or not. However, using 8·16 lb. as the weight per gallon of the non-volatile vehicle, I calculated the P.V.C. of paints Nos. 1, 2, 3, 4, 9, 41, 58, 66 and 67 to obtain an idea as to how the P.V.C. compared. These figures are as follows :

Paint	.	1	2	3	4	9	41	58	66	67
P.V.C.	%.	60·3	52·3	52·6	48·8	53·6	42·8	43·9	51·6	48·1

This type of information would be of value in a paper such as this, because closer comparisons could be drawn. In a series such as this, results do not necessarily conclusively indicate that one *pigment* is better than another, but only that one *formula* is better than another. For direct pigment comparisons a definite P.V.C. should be established and formulæ constructed accordingly. In this way one can definitely state that at a given P.V.C. one pigment is better than another.

I would suggest that in future exposure series several standard paints be included, so that a comparison of experimental formulæ may be made against these standard paints. The latter could be a government speci- fication paint, or any good commercial brand of paint which is now accepted in the trade for the application in question.

The method of rating the panels is excellent, and the merit figure is a very good method of comparing the total performance of the paints.

This paper is an excellent record of the exposure performance and stability of the formulæ involved. I hope that the above may be of some value in future tests, in which my interest would be continued.

Dr. GEORGE H. YOUNG (Mellon Institute of Industrial Research, Pitts- burgh, Pa., U.S.A.; Vice-Chairman, American Co-ordinating Committee on Corrosion) wrote: I have now had an opportunity to go over the highlights of this excellent study. Taken by and large, the findings are in excellent agreement with work along similar lines which we have been carrying on since 1940. This is pointed out (p. 293 P) in referring to Dr. Speller's paper before the Engineers' Society of Western Pennsylvania. As the authors know, Dr. Speller's paper was based almost entirely on work that we at Mellon carried out with him in connection with the lock system for the Panama Canal. I am also in complete accord with the remarks in paragraph (ii) on p. 293 P anent adverse weather at the time of painting. Like the authors, we are actively seeking for remedial techniques.

One or two other points deserve special comment:

(1) On p. 282 P the authors comment that " the behaviour of No. 85 may have been enhanced by the fact that the specimens to which it was applied were treated with an inhibitive wash." There is no " may " about this ! Re-exploration over the more typical surfaces employed by the authors will almost certainly show this rating to be too high.

(2) The findings that zinc-dust paints are poor need clarification. Under the authors' conditions, where no " barrier coat " was employed, their results are predictable; where Zn–ZnO paint is used as the primer, with an intermediate coat (such as straight iron oxide) before applying the anti-fouling coat, this is one of the best underwater paints, even in salt water.

In this connection, no one over here seriously attempts to package a " ready-mixed " zinc-dust paint. We use a two-compartment container, with labelled instructions to stir in the zinc dust, stand overnight and apply in the next 48 hr. This is standard commercial practice; I am surprised that the authors' retained shelf samples didn't blow the lids off.

(3) We can confirm the authors' findings about the beneficial effect of inert extenders. They got a 40% efficiency increase. In *anti-fouling paints* the difference is even more marked. A paper from this laboratory giving quantitative data and discussing the phenomenon has just been published.[1]

(4) I think the authors' single " chlorinated-rubber " vehicle is hardly representative. Most of the really superior chlorinated-rubber paints carry a sizeable alkyd modification. Our tests tend to confirm others that this type of vehicle is outstanding in sea water.

(5) I am interested in the formulating details of the two experimental anti-fouling compositions (Table IV.). As a matter of fact, I am going to prepare samples of them for comparison exposure tests at Daytona Beach, Florida. A quick calculation shows that the total toxic contents,

[1] G. H. Young, W. K. Schneider and G. W. Seagren, *Industrial and Engineering Chemistry*, 1944, vol. 36, p. 1130.

on a dry-film basis, are 34·5% for $AF8/42$ and 29·5% for $AF1/43$. While the authors are carrying what we would regard as an excessively high HgO content, these figures are squarely in the range of the familiar commercial bottom paints; if they last more than 6 months at Daytona I shall be surprised. All our tests show, as we have repeatedly emphasised, that a toxic loading in excess of 45–50%, dry-film basis, is necessary for prolonged anti-fouling life.

The authors comment that $AF1/43$ is an improvement over $AF8/42$. The analysis possibly explains this : Though the total toxic is somewhat lower, the doubled pigment-to-binder ratio, higher total solids (laying down a heavier film), higher inert content including asbestine, and, significantly, the higher rosin content of the binder are all conducive to better performance, as the authors have no doubt discovered. Even so, I doubt if $AF1/43$ is as much as 50% more efficient than $AF8/42$. It will be interesting to see how our tests on them check out.

(6) In conclusion, we agree that blue lead (basic lead sulphate) is a superior salt-water pigment.

Mr. R. J. LEDWITH (Cellon, Ltd., Kingston-on-Thames) wrote : We have read this paper with interest and would like to offer our comments on certain aspects of the work.

First, it is difficult to understand why at Caernarvon some, but not all, pigments were tested separately, and what motives prompted the selection of the pigment combinations (Table II.). Moreover, although in the Bakelite paints the pigment proportions by weight conform to the pigmentation code in the column headings (Table XXII.), yet in the paints formulated in Table XX. no such simple relation is apparent. In any case, would it not be preferable to make all pigment comparisons on a basis of pigment volume or of oil absorption ? Table XX. shows serious variations in the pigment/vehicle ratio, whether determined on a weight or on a volume basis.

In selecting the pigments, undue emphasis appears to have been laid on red lead combinations, at least when considered on purely technical grounds. On the other hand, chromate pigments received scant attention ; why were they merely " ear-marked for further study " (p. 282 P) rather than investigated fully ? The results on two of the five chromate paints (Nos. 84 and 85) were of doubtful value, owing to disparities in the panels.

According to Table XX., wide variations in the viscosity were tolerated. Not only would comparative results be rendered misleading by this, but in some cases the application of a suitable film thickness must have been unduly dependent upon the skill of the operator. In fact, the film thickness varied greatly, from 61 microns in the case of paint No. 2 to 134 microns for paint No. 5 (Table XXV.).

Viscosity, film weight and film thickness are interrelated aspects of a single practical problem. We feel that reasonably constant thickness of the applied films is highly desirable ; and the large variations in viscosity, which have so potent an effect and which could have been minimised, are unjustifiable.

With regard to the rating formula for deterioration, $B + 2F + 4R$,[1] publication of the separate assessments for blistering and flaking would have been of interest. The authors remark (pp. 311 P–312 P) on the difficulty of assessment caused by the use of a " disappointing " anti-fouling composition (p. 277 P), which was very thinly applied (Table XXIV.). This

[1] B is the blistering, F the flaking and R the rusting, expressed as percentages, on the two sides of the specimen.

particular difficulty could have been readily avoided, and more accurate evaluation of the factors B and F would have been possible even to the end of the immersion period.

Larger panels, for example, 24 in. $\times$ 12 in., would have been preferable, particularly in view of the lack of exact duplicates in the A series at Caernarvon, in which two types of pretreatment were included.

The description of the painting procedure given on pp. 275 P and 289 P is somewhat obscure, but it would appear that, in view of the variations in the drying time allowed for the first coat, some of the panels painted with two coats may not have been hard-dry before the application of the anti-fouling.

It is hoped that these protracted field tests have been, or will be, supplemented by accelerated and other laboratory tests, and that a description of these will be published. Possibly the results of previous laboratory work were the reason for selecting paint scheme No. 83 (Tables III. and VII.). No other reason is readily apparent why a different second coat should be used in this scheme, or why it should possess the formula chosen.

Consideration of the formulæ tested in series B at Emsworth prompts the criticism that the three pigment combinations (p. 287 P) were not sufficiently diverse to justify either the space occupied by the panels or the work involved. We suggest that more valuable information would have been gained by selecting three completely distinct types of pigmentation—for example, a lead pigment, a chromate, and a metallic pigment. Alternatively, considering the vast number of potential vehicles, it might have been preferable *at this stage* to restrict the pigmentation to a single combination and to use the full facilities for testing the maximum number of media. The field is so large that the selected 21 media, although diverse, necessarily fail to include many interesting possibilities. It would have been better to confine attention in this series to one type of vehicle, *e.g.*, synthetic-resin/oil varnishes, so that the variables, such as oil length, type of resin, oil and drier, and cooking schedule, could be explored satisfactorily.

On p. 313 P it is stated that the loss in weight was taken as the difference between the weights of the painted panels before exposure and after exposure and cleaning. It seems questionable whether these figures are of much value, compared with those obtainable by weighing the bare panels before painting and after removal of fouling, corrosion products and paint. In any event, a curious inconsistency emerges when one considers the use made by the authors of the loss-in-weight figures so laboriously collected. On pp. 317 P–318 P loss-in-weight determinations apparently justify the suggestion that the series A panels compare favourably with those of proprietary compositions discussed in the First Report of the Sub-Committee, and loss-in-weight figures are embodied in the total merit figure. On the other hand (p. 333 P), with series B " the correlation between the order of merit based on the loss in weight and that based on the index figure is poor," and " consequently, the loss in weight of the specimens has not been taken into consideration when assessing the results."

The foregoing criticisms are offered in the hope that they may be found of some interest, and all workers in this field will be grateful to the authors for the mass of valuable information presented in this paper.

AUTHORS' REPLY.

The AUTHORS, in reply, thank Mr. Jackson and Dr. Young for their contributions, and in reply to the former wish to say that the tests reported in their paper were the first of a series and were designed to be exploratory and to form the basis of further work. The paints were to be regarded rather as prototypes and as showing possibilities and trends to be further developed. In a subsequent series of tests, the results of which have not yet been published, due regard has been paid to what is agreed to be an important factor—P.V.C. It will be appreciated that under war conditions it was desired to spread the investigation over as large a number of pigments as possible; this in itself limited the number of tests which could be conducted on any one pigment. The weight per gallon (American) of the non-volatile portion of the modified phenol-formaldehyde medium was 8·2 lb. Mr. Jackson's suggestion that standard paints be included in exposure tests such as this was, in fact, adopted, but since the paints concerned were proprietary ones the results have not been reported.

The authors regard Dr. Young's statement that the results obtained in the United States of America substantiate their own with great satisfaction.

In reply to Dr. Young's various points :

(i) The benefits of phosphoric acid washes in general are, of course, well known, but the evidence in relation to the specimens treated with paint 85 did not of itself justify a dogmatic statement.

(ii) The use of a barrier coat over a zinc-dust/zinc-oxide primer is a helpful suggestion. The authors appreciate Dr. Young's remarks concerning the packaging of zinc dust in double containers (a practice in limited commercial use in Great Britain), but there is a certain prejudice against this here, where ready-mixed paints are preferred.

(iii) The authors are in general agreement with the views of Dr. Young and his colleagues concerning the important rôle played by inert extenders in certain types of anti-fouling paints.

(iv) The merits of chlorinated rubber are understood, but at the time when these tests were planned the supply position was at its blackest, and the possibility of obtaining commercial amounts seemed remote. The fact that one rubber medium was included testifies to the authors' appreciation of its merits; they do not defend their choice of the particular combination tested.

(v) The toxic contents of the two anti-fouling compositions $AF8/42$ and $AF1/43$ should have proved sufficient on the basis of previous tests to ensure an anti-fouling life of six months *under the conditions of immersion at Caernarvon*. It is now considered that the reason why they failed to do so was that the composition of the paint media and the pigment/vehicle ratio were not correct.

(vi) The basic lead sulphate used was not blue lead but white basic lead sulphate.

The following points made by Mr. Ledwith appear to call for reply :

(i) As has already been pointed out, the field which it was desired to cover was so vast that it would have been impossible to cover it completely in one investigation. Some of the choices made may appear arbitrary, which indeed they are, but it is not intended to imply that the choices made were necessarily the only ones or even the best;

availability of materials played a large part in the final selection.   It should be pointed out that Mr. Ledwith's suggestion that chromate pigments received scant treatment is at variance with the fact that 18 of the 85 paints contained one or other of various types of chromate pigments.

(ii) The authors agree that in some cases there is an appreciable deviation between the actual formulation of the pigment mixtures and the values denoted by the symbolic reference to the paint.   Having regard to the fact that it was general indications rather than specific formulæ which were intended, such deviations are not serious.

(iii) Mr. Ledwith appears to assume that the application characteristics of paints with varying pigments and media, such as are employed in this test, are related to viscosity.   This is not correct. Moreover, it is doubtful whether the efflux time of the paints could have been controlled within very narrow limits, having regard to the wide variation in formulation involved.   In any case it has been demonstrated that the general conclusions are in no way affected by such variations. It may be added that this is probably the first paper of its type in which the film thicknesses have been recorded in this way, a fact which shows the authors' interest in this aspect of the problem and their appreciation of its importance.

(iv) Mr. Ledwith is correct in assuming that paint formulations Nos. 76–83 in 100% phenolic-resin media were based on previous experience and laboratory work.

(v) The authors agree that, as it turned out, the three pigment combinations used in the Emsworth tests might have been varied with advantage.

(vi) The main burden of Mr. Ledwith's criticism of the Emsworth tests is that various other factors were not investigated.   As it was, the amount of work involved was great, and it would have been impracticable to explore the other possibilities suggested by him.

(vii) The probable reason why the loss-in-weight determinations at Emsworth were not a satisfactory index of the failure of the paints is that, owing to the fact that the specimens were only $\frac{1}{8}$ in. thick, considerable attack and rusting took place at the edges.

DEVELOPMENTS IN THE DESIGN AND USE OF SIDE-BLOWN CONVERTER PLANTS.[1]

By P. C. FASSOTTE (Iron and Steel Control).

(Fig. 1 = Plate XXVII.)

Summary.

A shortage of hematite iron at the time when new converter plants had to be erected led to a re-assessment of the relative importance of the silicon and carbon reactions in the process. It was established that the carbon reaction leads essentially to the formation of carbon dioxide. The temperature increment derived from this carbon combustion is such that this reaction may be relied upon principally to produce the final steel temperature. Plants were therefore built in such a way that silicon could be largely dispensed with, with the concomitant elimination of hematite from the cupola charges. The operation of such a plant is discussed.

Introduction.

THE manufacture of steel castings is one of the sections of the steel industry which has required considerable expansion during the war and this has entailed the erection of a number of new plants. Some of them have been equipped with electric furnaces, but, for reasons beyond the scope of this paper, others have been provided with converter plants. At the time when this development was planned the supply of ores suitable for the manufacture of hematite irons suddenly became precarious, and it was therefore necessary not only to economise in the use of hematite iron but also to explore unorthodox methods of steel production.

More than half the steel used in British foundries before the war was produced in converters. The ratio of scrap to pig iron used in the various plants differed widely, depending on the location of the foundry and the construction of the unit; it averaged about 50% throughout the country. On account of its moderate cost, hematite iron was used liberally and in most plants was relied upon exclusively to produce the silicon content aimed at in the iron. This silicon content also varied considerably but the average was about 1.5%.

Experiments on the Relative Importance of the Silicon Reaction.

Years of converter use had crystallised the opinion that molten iron had to contain 1.3% or more silicon for successful operation of the process. It was generally regarded as fundamental that the exothermic reaction of silicon and oxygen was the main determinant of the final steel temperature and that therefore this reaction,

[1] Received March 1, 1944.

credited with a heat value of some 7000 kg.cal., could not be dispensed with in converter operation. The carbon reaction was discounted as a heat producer owing to the belief, fostered by the text books, that most of the carbon was burned into carbon monoxide, a reaction yielding only 2430 kg.cal. and negative from a heat-increment point of view. Little notice was taken of the carbon-dioxide reaction, yielding 8100 kg.cal., as this reaction was not considered to take place to an appreciable degree.

These beliefs had become deeply rooted and almost axiomatic. Yet observations made of a large number of plants operated in widely varying conditions and in different countries had thrown doubt on these accepted theories. Whereas some side-blown converters were being operated with silicon up to 2%, others had been known to work with irons containing only 0·5–0·7% of silicon and yet produce steel sufficiently hot to make small and intricate castings. There was a strong suspicion, therefore, that too much stress had been laid on the significance of the silicon reaction. The following experiments were accordingly planned in order to ascertain its true importance :

(1) A charge of normal cupola iron (carbon 3·2%, silicon 1·3% and manganese 0·5%) was introduced into a converter and blown in the ordinary way. When the carbon flame appeared the blow was stopped and the metal poured into a ladle. The temperature of the metal was then 1535° C. and the analysis 2·7% of carbon, 0·15% of silicon and 0·14% of manganese. The metal was cooled in the ladle and poured back into the converter when the temperature had dropped to 1435° C. The blast was put on again and the blow proceeded normally despite the disappearance of the silicon. The ultimate temperature of the steel was 1650° C., an increment of 215° C.

(2) A charge of low-silicon iron (carbon 3·2%, silicon 0·21% and manganese 0·3%) melted in an electric furnace was introduced into a converter at a temperature of 1385° C. The blow was normal and the final steel temperature was 1590° C., an increment of 205° C.

(3) A charge of low-silicon iron melted in an electric furnace (carbon 3·26%, silicon 0·17% and manganese 0·18%) was introduced into a converter at 1440° C. and blown into steel with a final temperature of 1630° C., an increment of 190° C.

In view of the small amount of silicon contained in the irons used in these experiments, the temperature increments could only be explained by the fact that the carbon combustion was essentially a carbon-dioxide reaction. In this respect, the side-blown converter appears to work differently from the bottom-blown type, where the passage of gases through layers of metal rich in carbon favours the production of carbon monoxide. The gases escaping from the side-

blown converter were analysed and Table I. gives the results.   The gas samples were taken some 9 in. below the exit of the converter.

TABLE I.—*Analyses of Gases Escaping from the Converter.*

Samples taken 9 in. from nose end.

	First Heat.			Second Heat.			Third Heat.		
Weight of charge. Cwt. . .		75			65			65	
Silicon content. % . . .		0·18			0·32			0·6	
Duration of blow. Min. . .		12			12			17	
Gas analyses after min. :	1.	5.	9.	2.	7.	11.	1.	7.	11.
Carbon dioxide. % . .	4·0	9·8	12·8	12·0	12·2	4·2	4·2	10·0	9·8
Oxygen. %	10·4	2·6	2·8	2·4	0·9	10·2	5·6	4·4	5·0
Carbon monoxide. % .	0·2	0·2	0·2	0·2	Nil	Nil	0·1	0·1	Nil
Nitrogen. % . . .	85·4	87·4	84·2	85·4	86·9	85·6	90·1	85·5	85·2
Blast volume. Cu. ft. per min. .	4200	4200	4000	4300	4500	4500	4200	4200	4200

Another series of samples were taken by drilling a hole in the converter body and through the lining, at a point 4 ft. above the tuyeres.   Table II. gives the analyses of these samples.

TABLE II.—*Analyses of the Converter Gases 4 ft. above the Tuyeres.*

	First Heat.			Second Heat.			Third Heat.			
Weight of charge. Cwt. .		56			56			60		
Carbon content. % .		2·92			3·14			2·98		
Silicon content. % .		0·46			0·31			0·66		
Duration of blow. Min. .		13			11			11		
Gas analyses after min. :	3.	6.	10.	3.	6.	11.	1.	4.	8.	10½.
Carbon dioxide. % .	4·0	6·2	14·2	8·0	6·6	10·8	6·4	12·0	12·8	12·4
Oxygen. % . . .	10·6	3·0	1·6	0·8	4·2	0·4	0·3	0·1	Nil	0·6
Carbon monoxide. % .	1·0	0·4	2·6	0·8	0·4	1·4	0·9	0·7	0·2	0·1
Nitrogen. % . .	84·4	90·4	81·6	90·4	88·8	87·4	92·4	87·2	87·0	86·9
Blast volume. Cu. ft. per min.	3500	3000	3000	3580	3050	3050	3200	2900	2900	2900

Attempts were also made to analyse the gases at a point a few inches above the tuyeres, but these were abortive as the aperture was quickly blocked by projections.

Gas analyses were also taken in other plants.   They generally confirmed that carbon dioxide is overwhelmingly prevalent.   Yet under certain working conditions appreciable quantities of carbon monoxide can be present in the exit gases and this feature has been observed particularly where the blowers are under-sized.

The function of the silicon reaction now appeared in its true perspective.   It is essentially a kindling agent.   Its principal purpose in side-blown converter practice is to make up the difference between the temperature of the iron introduced into the converter and the temperature at which the carbon reaction starts freely.

Conclusions from Experimental Data.

The experimental work warranted the following conclusions :

(a) In the side-blown converter the bulk of the carbon is transformed into carbon dioxide, provided that there is adequate blast volume.

(b) Irons containing from 2·7% of carbon upwards, with only a negligible silicon content, can produce a temperature increment of over 200° C.

(c) The carbon-dioxide reaction is capable of making up the difference between an iron temperature of, say, 1450° C. and the steel temperature required by the steel foundry.

(d) Silicon in the iron can be dispensed with, provided that the metal is sufficiently hot at the commencement of the blow.

It is a well-known fact that the affinity of carbon for oxygen increases with temperature and becomes particularly pronounced at temperatures exceeding 1450° C. If, therefore, iron were supplied to the converter sufficiently hot for the carbon reaction to start immediately, then silicon could be dispensed with, with the concomitant elimination of the hematite and ferro-silicon from the cupola charges. It became a matter of substituting for heat chemically produced in the converter by the silicon combustion, heat physically imparted to the iron prior to the conversion process. To achieve this end a furnace had to be introduced between the cupola and converter in which the iron could be brought up to the temperature at which the carbon reaction starts. If large enough, such a furnace would also act as a mixer and reservoir for hot metal, which would make it possible to operate the cupola independently of fluctuations in the demand for steel and to secure greater uniformity in the iron and efficiency in the converter operation.

Plants were designed on the above lines and Fig. 1 shows the general arrangement of such a plant. The ensuing remarks apply to this plant specifically.

Description and Operation of the Side-Blown Converter Plant.

In designing the cupolas care was taken to provide them with deep wells in order to favour carbon pick-up, as the charges were to be composed of steel scrap only. The metal produced by the cupolas has approximately the following composition :

Carbon. %.	Silicon. %.	Manganese. %.	Sulphur. %.	Phosphorus. %.
2·7–3·2	0·05–0·2	0·3–0·7	0·11–0·18	0·03–0·07

After it has been desulphurised the iron is transferred to the mixer, the temperature being 1280–1380° C.

The rotary mixers have a nominal capacity of 12 tons, but may reach 25 tons, depending on the degree of wear of the linings. They are fired by anthracite and the calorific input is such that the iron can be raised to the required temperature at the rate

PLATE XXVII.

Stock-yard bay. Converter & furnace bay. Blower house.

Cupola charging bay. Converter & furnace bay. Pulverised-fuel plant.

Charging bay. Converter & furnace relining bay. Brick store.

7·5-ton E.O.T. charging crane.

10-ton E.O.T. crane.

7·5-ton E.O.T. charging crane

7·5-ton E.O.T. crane.

To foundry

Pulverised-fuel plant.

No.1 No.2 No.3 No.4

Converters.

Rotary furnaces.

Converter relining pit.

Furnace relining pit.

No.1 No.2 Cupolas. No.3 No.4

7·5-ton E.O.T. magnet crane.

7·5-ton E.O.T. magnet crane.

Stock yard.

7·5-ton E.O.T. charging crane.

7·5-ton E.O.T. charging crane.

FIG. 1.—General Arrangement of a Side-Blown Converter Plant.

of 17–18 tons per hr. The fuel consumption is 80 lb. per ton of metal. After it has been superheated the iron is transferred to the converters in batches of 56–70 cwt. The mixer is continually being refilled by desulphurised cupola metal, usually in lots of 5 tons.

The silicon content in the metal charged into the converter approximates to 0·05–0·2%. Iron containing as little as 0·05% of silicon has been blown successfully and yielded steel sufficiently hot for foundry requirements. As the castings produced in this plant have a wall thickness of 0·3 in., it will be realised that quite hot metal is required. Although in principle the converters work with silicon-free iron, in practice small amounts of ferro-silicon are used for minor temperature adjustments. If, for instance, the temperature of the iron is judged to be on the low side, if the converter has been standing for some time before the new charge is introduced or if a particularly high temperature is required in the steel, ferro-silicon additions are made in the converter. For a week's operation entailing the use of 1085 tons 10 cwt. of liquid iron, the ferro-silicon consumption (75% silicon) is 4 tons 10 cwt. 3 qr. 18 lb., representing an average addition of 0·28% of silicon to the converter charges.

Desulphurisation.

As no pig iron is charged into the cupolas, a high coke ratio is required (6 : 1), which involves a relatively high sulphur content in the iron (from 0·11% to 0·18%). When desulphurising with sodium carbonate in the normal manner the steel frequently showed a sulphur content upwards of 0·06%. Selection of a more suitable lining material for the ladle improved matters. It was then found that by using two ladles and pouring slag and metal from the first to the second ladle the efficiency of the process was increased. In Table III. the complete analyses of a shift's operation of the plant are recorded. Heats Nos. 9139–9160 were desulphurised in ladles lined with firebrick and gave an average sulphur content of 0·0367%. The subsequent heats were desulphurised in ladles lined with basic material and gave an average sulphur content of 0·0272%. Assuming that the iron used in the latter heats had an original sulphur content of 0·13%, there was a sulphur elimination of 79%. The high sulphur content of the iron produced by the process is therefore not necessarily detrimental; in fact, steel has been produced with a sulphur content below 0·02%.

Duration of the Blow.

The rotary mixers were not ready to operate when the plant was started up and for a time steel was made in the normal Tropenas manner, using a proportion of pig iron and ferro-silicon in the cupola to give iron with upwards of 1% of silicon. With these charges, the converter blows lasted an average of 18 min. When the rotary

TABLE III.—*Analyses of the Steels Obtained on One Shift.*

Heats Nos.	T.C. %.	Si. %.	Mn. %.	S. %.	P. %.
9139	0·23	0·35	1·72	0·052	0·075
9140	0·22	0·27	1·64	0·046	0·076
9141	0·22	0·31	1·68	0·044	0·075
9142	0·24	0·27	1·64	0·038	0·072
9143	0·22	0·32	1·64	0·042	0·068
9144	0·23	0·26	1·50	0·036	0·067
9145	0·22	0·27	1·58	0·038	0·069
9146	0·22	0·24	1·60	0·036	0·068
9147	0·23	0·29	1·52	0·038	0·066
9148	0·21	0·27	1·60	0·032	0·067
9149	0·23	0·28	1·60	0·032	0·066
9150	0·21	0·29	1·62	0·036	0·063
9151	0·22	0·28	1·70	0·030	0·064
9152	0·22	0·23	1·46	0·038	0·064
9153	0·21	0·25	1·46	0·040	0·062
9154	0·21	0·25	1·42	0·036	0·059
9155	0·21	0·32	1·54	0·034	0·057
9156	0·21	0·24	1·54	0·032	0·058
9157	0·21	0·23	1·42	0·018	0·058
9158	0·21	0·30	1·46	0·038	0·057
9159	0·22	0·29	1·60	0·036	0·059
9160	0·21	0·24	1·38	0·036	0·057
9161	0·22	0·28	1·50	0·028	0·057
9162	0·21	0·28	1·46	0·030	0·058
9163	0·21	0·33	1·50	0·028	0·058
9164	0·23	0·27	1·52	0·028	0·060
9165	0·21	0·32	1·48	0·026	0·061
9166	0·21	0·29	1·44	0·026	0·059
9167	0·22	0·30	1·44	0·028	0·061
9168	0·22	0·29	1·44	0·026	0·069
9169	0·21	0·31	1·42	0·028	0·058
9170	0·23	0·25	1·46	0·028	0·059
9171	0·21	0·34	1·64	0·026	0·059
9172	0·23	0·27	1·50	0·026	0·061
9173	0·22	0·37	1·48	0·028	0·060
9174	0·24	0·27	1·44	0·024	0·060
9175	0·23	0·35	1·44	0·030	0·059

mixers were brought into use with irons low in silicon, the average duration of the blow was reduced to 11 min.   The immediate result was that two converters instead of three were able to feed the foundry with the requisite amount of steel and this added flexibility was accompanied by a reduction in the labour cost.

Slagging.

A favoured deoxidation procedure in converter foundries is to remove the bulk of the slag from the converter before any deoxidising agent is introduced into the bath.   When high-silicon irons are used, converter slags are heavy and the removal of the slag is a slow and difficult operation.   With low-silicon iron there is less slag, it is less viscous and its removal is both easier and faster.

Converter Linings.

It was realised that with low-silicon irons there would be almost no SiO_2 produced and that the converter linings were likely to be attacked severely by metallic oxides. The first few blows after the mixers were put into operation provided confirmation. Silica sand was then introduced in the empty converter before the liquid iron, so as to provide the SiO_2 required to balance the oxides. Not only did this addition of sand stop undue corrosion, but it improved the life of the linings remarkably. When operating the plant in the normal Tropenas manner, the inner linings of the converter gave an average life of 60 heats without patching. When using low-silicon irons together with a sand addition, the inner linings made up of bricks from the same source and also without patching gave an average life of over 200 heats. This increased life of the linings, however, is partly attributable to the reduced blowing time.

To ascertain the effect of sand additions on the composition of the slags, samples were taken during the converter operation in another foundry where high-silicon irons are used and the plant is such that the converter operation is of long duration. These metal and slag analyses are recorded in Table IV.

TABLE IV.—*Metal and Slag Analyses during the Blow (Tropenas Plant).*

Converter charge : Carbon 2·54%, silicon 1·46%, sulphur 0·079%, phosphorus 0·047%, manganese 0·27; 75 cwt. Temperature of iron : 1280° C. Total blowing time : 48 min.

	Time from Commencement of Blow—				
	11 min.	18 min.	28 min.	37 min.	Finish of Blow.
Analysis of metal :					
Carbon. %	2·66	2·44	2·18	1·38	0·05
Silicon. %	1·26	1·08	·0·50	0·34	0·06
Manganese. %	0·19	0·15	0·08	0·06	0·03
Sulphur. %	0·078	0·070	0·067	0·059	0·054
Phosphorus. %	0·047	0·050	0·052	0·049	0·045
Analysis of slag :					
Silica. %	38·1	40·95	46·15	55·35	66·65
Ferrous oxide. %	54·5	52·28	47·61	37·67	27·09
Alumina. %	3·9	3·20	2·80	3·70	3·60
Manganous oxide. %	3·29	3·36	3·36	3·07	3·39
Lime. %	0·50	0·40	0·30	0·30	0·30
Magnesia. %	Trace	Trace	Trace	Trace	Trace
Temperature (immersion thermocouple). ° C.	1310	1370	1560	1685	1690

It is interesting to compare these results with samples of slag taken from one of the converters of the plant described in Fig. 1

TABLE V.—*Slag Analyses during the Blow* (*Low-Silicon Iron*).

Converter charge : Carbon 2·7%, silicon 0·2%, manganese 0·35% ; 70 cwt.
Sand (70 lb.) put into the converter prior to the introduction of the iron.
Total blowing time : 14 min.

	Time from Commencement of Blow—				
	2 min.	·4 min.	6 min.	8 min.	14 min.
Silica. %	55·4	54·2	54·0	56·0	60·0
Alumina. %	3·6	3·5	3·7	3·6	3·1
Ferrous oxide. %	23·2	25·7	25·1	25·2	22·5
Ferric oxide. %	7·5	4·1	4·7	4·0	3·3
Manganous oxide. %	10·1	12·2	12·0	10·9	10·7

(*see* Table V.).   It will be noted that in the case of the normal
Tropenas plant there is a constant deficiency of SiO_2 to balance the
oxides until the operation is well advanced, which is not the case with
low-silicon irons when a sand addition has been made to the converter.
It is also noteworthy in Table IV. that the formation of FeO and
MnO is practically instantaneous ; therefore the timely presence of a
sufficiency of SiO_2 in the slag, namely, at the beginning of the blow,
is all important.

Metallic Loss.

It was expected that irons low in silicon and manganese and
blown in shorter time would not be subject to the same amount of
metallic loss as is encountered in normal side-blown converters.   This
anticipation was verified in practice.   When worked in the Tropenas
manner, the blowing loss in the converter was about 9%, which
compared favourably with the average metallic loss throughout
the country.   With low-silicon irons and reduced blowing time the
metallic loss in the converter, checked as carefully as possible over
a number of heats, averages between 5% and 6%.

No metallic loss is experienced in the rotary mixers.

Phosphorus.

It is a well-known fact in converter foundries that, despite the
care which is taken, wrought or cast iron occasionally finds its way
into the cupola charges.   Moreover, the phosphorus content of steel
scrap can vary considerably, particularly in a plant like the one
under review which has to work with unselected scrap.   In such
conditions, the phosphorus content of the final steel can sometimes
be very high and when this plant was worked in the Tropenas
manner the final steel occasionally showed a phosphorus content
well above 0·1%.   These fluctuations in the phosphorus content
have been levelled out by the mixers and, as will be seen from
Table III., the phosphorus variation in the steel produced is
extremely small after the first few heats.

Every day the first few heats tapped from the cupola show a higher phosphorus content than during the remainder of the day. The phenomenon is explained by the phosphorus pick-up from the ash of the initial coke charge (the phosphorus content of the coke being 0·3%).

There is, however, a more important aspect to the question of phosphorus content. Attempts to dephosphorise iron in the cupola in the presence of silicon and manganese have failed, as selective oxidation of these elements takes place before any impression is made on the phosphorus. When using all-steel charges in the cupola, however, the silicon and manganese contents of the iron are negligible and conditions are fulfilled wherein dephosphorisation in the cupola becomes theoretically possible, provided that a basic lining is used. Experimental work in this direction is in hand.

Physical Properties of the Steels Obtained.

The typical test results given in Table VI. will enable the physical properties of the steels made by this process to be compared with similar steels made by other methods.

TABLE VI.—*Physical Properties of Three of the Heats Obtained.*

Clover-leaf test-blocks treated at 940° C. for ½ hr. and air-cooled.

Heats Nos.	Analyses.					Physical Properties.						
	C. %.	Si. %.	Mn. %.	S. %.	P. %.	Yield Point, Tons per sq. in.	Maximum Stress, Tons per sq. in.	Elastic Ratio. %.	Elongation. %.	Reduction of Area. %.	Izod Value. Ft.lb.	Brinell Hardness No.
8131	0·20	0·27	1·26	0·032	0·064	27·2 / 27·2 / 27·2	39·6 / 40·0 / 40·0	68 / 68 / 68	22 / 27 / 26	26·31 / 43·41 / 36·56	25, 26, 30—27 / 41, 42, 43—42 / 33, 33, 33—33	}163
8129	0·19	0·27	1·08	0·034	0·063	24·8 / 25·8 / 25·6	36·0 / 36·0 / 36·0	69 / 72 / 71	30 / 31 / 30	43·41 / 40·72 / 43·41	46, 46, 46—46 / 44, 51, 46—47 / 46, 44, 45—45	}156
8119	0·19	0·33	1·23	0·040	0·064	26·8 / 26·0 / 26·4	37·2 / 37·2 / 39·6	72 / 71 / 66	28 / 29 / 27	42·07 / 43·41 / 36·56	40, 40, 43—41 / 46, 48, 47—47 / 37, 37, 37—37	}156

Credits and Debits.

The advantages of the process may be summarised as follows :

(1) Elimination of hematite and ferro-silicon from the cupola charges.

(2) Reduced consumption of ferro-silicon in the converter.

(3) Appreciable reduction of blowing loss in converter.

(4) Increased flexibility and production through reduction in blowing and slagging time.

(5) Longer life of converter linings.

(6) Less variation in phosphorus contents and in final steel analyses.

(7) More continuity in cupola operation.

(8) Reduced quantity of converter slag and easier removal.

The process has the following disadvantages which must not be overlooked :

(1) Considerable increase in capital expenditure due to the cost of the mixers and the provision of a heavy crane to change the mixer bodies.

(2) Heavier structure needed to support this crane and larger area required by the melting plant.

(3) Higher coke ratios needed in the cupola for melting all-steel charges.

(4) Greater wear on cupola refractories.

(5) Extra labour and upkeep entailed by the operation of the mixers.

(6) Fuel and lining costs of the mixers.

In the particular plant under review, the items of increased cost are more than offset by the savings due to cheaper charges, reduced metallic loss and improved performance of converter refractories.

The main purpose of the unconventional design, namely, the conservation of hematite iron, has been fully achieved.

CORRESPONDENCE.

Mr. C. W. D. TOWNSEND (Messrs. Thos. Firth and John Brown, Ltd., Scunthorpe) wrote : I feel that the conditions and circumstances which led up to the introduction of a rotary furnace in conjunction with cupolas and converters should not be lost sight of. The conception was a bold one to meet the anticipated shortage of hematite iron and ferro-silicon.

The theory that the silicon could be dispensed with, provided that the iron from the cupola was superheated by pulverised fuel in a rotary furnace, was untried. Some doubts were expressed by many experienced converter steel makers as to the results until an experiment was carried out by blowing the silicon out, then pouring the metal into a ladle and allowing it to approximate to the condition as regards analysis and temperature in which it was intended to take the metal from the rotary furnace in order to recharge it into the converter for continuing the blow to remove the carbon.

This experiment proved entirely satisfactory and the heat finished well and was suitable for pouring thin castings.

As the results from the plant erected and described in the paper have corroborated those obtained from the above experiment the sponsors of the new system have been amply justified in their enterprise and are worthy of congratulations on their foresight and courage.

Colonel WM. ROUTLEDGE (The Stanton Ironworks Co., Ltd., near Nottingham) wrote : The amount of data available on side-blown converter practice is very meagre. We found this out when we commenced operations—in fact, we were not able to obtain anything that we could utilise for the training of our people in the early days of our plant.

I have been intimately connected with the plant described by the author since its inception, and can say that we have operated very closely on the lines brought out in the paper for the past two and a half years, with, I think, quite reasonable success.

This plant is producing at the present moment something like 1200 tons of steel per week, both of the analysis given in the paper and soft steel. There is no doubt that the melting plant fits in well with our mass-production foundry and gives us the continual flow of hot regular steel necessary for the production of thin-walled castings. Whether such a plant would be of such value in a jobbing foundry, even on an extensive scale, is another matter, on which I feel that I am not competent to express an opinion. Steel founding has not been my business in life, and what we have learned on our plant has been learned during the past three years.

There is a fact, however, which Mr. Fassotte has not taken into consideration when he speaks of costing ; it depends very much on the prices of hematite iron and steel scrap, which vary from time to time, and there are periods when it may be more reasonable to use iron in the place of steel scrap. At the present moment we have definitely proved that it is cheaper to operate the plant under the conditions described with 100% scrap, using the rotary furnace, than with, say, 20% pig iron and 80% steel scrap at the cupola. This saving can, of course, be mitigated by too frequent renewal of the rotary-furnace lining, which is fairly costly. There is definitely a saving in the process after the rotary furnace has passed through 2000 tons over the lining. We have got this figure up to over 6000 tons and the results are obvious.

I would like to reciprocate the acknowledgments at the end of the paper on my firm's behalf. We could not have wished for a more

enthusiastic collaborator in building up the data which produced this paper.

Mr. S. SPRAY (The Stanton Ironworks Co., Ltd., near Nottingham) wrote : As one connected with the operation of a plant as described in the paper, I can confirm the efficiency of the process, and offer congratulations to the author for the painstaking way in which it was built up from theory to large-scale mass-production practice. It is bound to have far-reaching effects, even on cupola design, as the desirability of high carbon in the metal charged to the converter obviously calls for a cupola with a deep well to give a maximum and regular carbon pick-up to the charge, especially when high-proportion steel mixtures are used.

The inclusion of the rotary furnace is a very economical proposition when used for high outputs on a mass-production scale, but the benefits would have to be carefully studied before its application to intermittent jobbing work. There appears to be no reason, however, why such work should not be so planned that a short blow in the cupola, with its resulting economies, should not be run, and the rotary furnace used as a holding furnace until the metal was required at the converters.

There has been some discussion as to the benefits derived from the sand addition to the converters before they were charged, but at the particular plant of which I have knowledge there is no doubt of its value in increasing the life of the converter linings. Before its use, a life of 60 heats was normal, but immediately the sand addition was put into operation the life increased to 140 heats, whilst improvements in the quality of refractories have since resulted in a life of 250–300 heats for the inner veneer lining. The presence of unconverted sand grains in the converter slag has been mentioned. I should not consider that this is an argument against its use, but rather an indication that sufficient had been added to ensure minimum iron-oxide attack on the converter lining.

It would appear that the best time to add the sand is immediately before charging the converter, not immediately at the end of the blow, especially if there were to be some delay in charging up for the next blow.

With regard to desulphurisation, most steel foundries have experimented with various ladle lining materials, and, although basic materials were tried in the plant now being discussed, various factors caused the return to firebrick linings. With the double-pouring technique a regular sulphur reduction of 80% is obtained with 30 lb. of soda ash per ton of metal treated from an average content of 0·170%. During a recent period when the normal brand of coke was not available the cupola metal had a sulphur content of 0·250%, owing to the use of another brand. This was adequately dealt with, using 35 lb. per ton of soda ash with double pouring, the final steel having less than 0·045% of sulphur. The rotary furnace between the cupola and converter is very useful at this stage, as any excessive temperature loss during desulphurisation can be made up.

Dr. J. H. WHITELEY (Consett Iron Co., Ltd., Consett) wrote : When reading this valuable paper, it occurred to me that the oxidation of iron itself in the converter might increase as the silicon content of the charge was reduced and, if so, the extra heat liberated would tend to counterbalance the lack of silicon. I therefore examined the data given in Tables IV. and V. to see whether any evidence was to be had in that direction. Assuming that very little silicon was carried away by the iron oxide in the gases, the weight of slag can be calculated from the

amount of silicon oxidised and the silica content of the slag. The weight of FeO retained by the slag can then be found. The figures obtained are given in Table A.

TABLE A.—*Weight of Slag Calculated from Silicon Oxidised.*

	Silicon Oxidised. %.	SiO₂ Formed. Cwt.	Weight of Slag. Cwt.	Weight of FeO in Slag. Cwt.
Table IV. : 18 min. . .	0·38	0·61	1·49	0·78
Finish of blow .	1·4	2·25	3·38	0·916
Table V., finish of blow .	0·2 *	$\left\{ \begin{array}{l} 0\cdot30 \\ 0\cdot62 \text{ sand} \end{array} \right\}$	1·53	0·40

* Assumed figure.

Now, when the quantity of manganese oxidised is taken as the basis of calculation, a much greater weight of slag appears, as is shown in Table B. The difference may be attributed to the manganese which is oxidised and driven off during the blow, and, if so, this difference may be taken as a rough indication of the extra quantity of iron so lost, for the manganese contents of the two charges are of the same order. Thus, it will be seen from the slag-weight ratios given in the last column of Table B

TABLE B.—*Weight of Slag Calculated from Manganese Oxidised.*

	Manganese Oxidised. %.	MnO Formed. Cwt.	Weight of Slag. Cwt.	Ratio of Weight of Slag to that in Table A.
Table IV. : 18 min. . .	0·12	0·116	3·45	2·32
Finish of blow .	0·24	0·232	6·84	2·02
Table V., finish of blow .	0·30 *	0·273	2·55	1·67

* Assumed figure.

that considerably more iron was blown away in the Table IV. cast than in that of Table V. Further, more iron oxide was also retained by the slag, so that the data given by the author would seem to support his statement that the metallic loss is less with low-silicon irons, but why that should be so is not at all clear.

Mr. E. J. BROWN (Messrs. Hadfields, Ltd., Sheffield) wrote : On reading the paper, one is inclined to get the impression that silicon does not matter in the blow; actually, of course, it performs an important function by its combustion in ordinary practice, by causing a definite increase in temperature. The usual overall temperature increment is in the neighbourhood of 400° C., being very roughly from 1280° C. to 1680° C. The increments in temperatures quoted as a result of the blow are those resulting from an extremely hot iron, that is, much hotter than is usually obtained from a cupola, and a low finishing temperature for the blown metal. The result is an increment of about 200° C. I suggest that a finishing temperature of 1595° C. is too low for anything but heavy foundry castings.

No mention is made as to how these temperatures were taken, but it is assumed that these are measurements made by the use of the immersion type of pyrometer. As a result of some experience in carrying out these,

it can be stated that it is no easy matter, owing to physical difficulties, to obtain accurate results from the blown metal. It would seem that the paper would be more complete with some details regarding the methods employed.

Mr. Fassotte states that silicon acts as a kindling agent; therefore, it may be assumed that in ordinary practice, using cupola-melted iron without silicon, it is impossible to blow. Is this so?

It would have been interesting to have included the actual temperature increase produced in the rotary furnaces; in fact a complete temperature log would not be out of place.

In conclusion, in consideration of post-war exploitation of the process—that is, running a steel foundry with output limitations—is it feasible to work a day turn only and hold over a charge in the rotary furnace overnight in order to make a flying start the following morning?

Dr. A. H. B. Cross (The Brown-Firth Research Laboratories, Sheffield) wrote : It is a good thing that we should, from time to time, take stock of our inherited ideas of metallurgical processes and ask ourselves whether these ideas still represent the facts as we see them. Mr. Fassotte has done this for us with regard to the side-blown converter process. As the plant to which he refers is operating with considerable success, I will confine my remarks to technical aspects of a manifestly successful operation.

The oxidation of carbon in the converter charge has been depicted by analyses of the converter gases, of which the sampling is not altogether simple nor are the results easy to interpret, as essentially a carbon to carbon dioxide reaction. It has long been known that the tendency for carbon to form carbon dioxide actually diminishes somewhat whilst the formation of carbon monoxide occurs appreciably more readily with increasing temperature. This fact should not be overlooked in considering the thermal value of the carbon oxidised. The first two heats recorded in Table II. of the paper differ in this respect from the remainder.

Whilst it has been shown that iron containing very little silicon can be blown satisfactorily to produce sufficiently hot steel for some purposes, the small amount of ferro-silicon used at the plant in question contributes 0.28% of silicon to the converter charge, which can then hardly average as low as $0.1–0.2\%$ of silicon and, from available information, appears to be nearer 0.5% of silicon. Such an amount of " kindling " agent should be assigned its appropriate heat value in any consideration of the facts presented in the paper.

The relatively small amount of silicon available for oxidation (compared with average side-blown practice) and the long life of the converter linings undoubtedly indicate reduced slag weight per charge. But the average slag composition is fairly typical of normal practice and observations at the plant do not suggest that the slag is appreciably less viscous. Recent analyses of slags from a converter plant blowing 1.0% silicon iron (with and without sand additions before the blow) have shown silica contents ranging from 56% to 62%, manganese oxide $6–11\%$ and ferrous oxide $20–26\%$, compositions closely similar to those given in the paper and probably exhibiting similar temperature/fluidity relations.

Additions of sand to the converter before the blow have been tried at a number of plants with varying results. In some cases the advantages claimed by Mr. Fassotte with low-silicon irons have been confirmed; in others no advantage was realised and trouble through building-up of the converter lining near the bottom was experienced, the latter with both

low- and medium-silicon irons (1%). Where sand has been added the frequent observation of undissolved sand grains in the converter slag gives rise to some doubt as to the efficacy of this "mop" for iron and manganese oxides. Abnormal slag analyses are by no means unknown in plants where the addition is made, and slag silica contents in the vicinity of 80% have been recorded. It thus appears that some of the sand, at least, exists as a separate phase in the slag and is not effective in establishing the normal equilibria.

Mr. F. R. ATKIN (Messrs. Firth-Vickers Stainless Steels, Ltd., Wombwell, near Barnsley) wrote : It appeared to me, when examining the gas analyses in Tables I. and II., that the percentages of nitrogen were unduly high. Using the fact that nitrogen and oxygen are present in the air in the proportion of 79 volumes to 21 volumes, it is possible to calculate the amount of oxygen which was associated (in the air blown into the converter) with the nitrogen which now exists in the products of combustion. It is an equally easy matter to calculate how much of that oxygen would be necessary for the formation of carbon monoxide and carbon dioxide. When these two calculations are made it is found that there is quite a considerable amount of oxygen unaccounted for.

Take as a typical example Table I., first heat after 5 min., and, for simplicity, call percentages volumes, thus :

CO_2.	Oxygen.	CO.	Nitrogen.
9·8	2·6	0·2	87·4 volumes

Now, 87·4 volumes of nitrogen originally had associated with them 23·2 volumes of oxygen, only 9·9 volumes of which were used in the formation of carbon dioxide and carbon monoxide; 2·6 volumes of oxygen remain unchanged, leaving 10·7 volumes of oxygen unaccounted for. This means that, whereas 9·9 volumes of oxygen are used in oxidising carbon, 10·7 volumes of oxygen are left unaccounted for, and it can only be assumed that this oxygen is used in oxidising those elements which have a non-gaseous combustion product, viz., silicon, manganese, iron, &c.

Now, when all the analyses are similarly examined, it is found that the number of volumes of oxygen unaccounted for are on the average slightly greater than the number of volumes of oxygen used in oxidising carbon. This suggested to me that a substantial part of the temperature increment was due to the heat of formation of SiO_2, MnO and FeO, in view of the fact that the previous calculations had shown that at least as much oxygen is used for the formation of SiO_2, MnO and FeO as is used for the combustion of carbon, and that the heats of formation of those three compounds are comparable with that of CO_2.

However, when the total weight of solid oxidation products is calculated, it is seen that something is amiss; assuming an average charge of 60 cwt., of composition carbon 3·00%, manganese 0·30% and silicon 0·40%, then, if all the carbon is burned to CO, 2·4 cwt. of oxygen will be used (or, if CO_2 principally is formed, 4·8 cwt. of oxygen).

Now, at least as much oxygen is used in the oxidation of silicon, manganese and iron as is used for oxidising carbon; therefore at least 2·4 cwt. of oxygen are used for the former purpose (and more probably 4·8 cwt., if carbon dioxide is formed preferentially to carbon monoxide, as the paper suggests). Taking the case most favourable to the paper, viz., 2·4 cwt., of oxygen, 0·27 cwt. of oxygen are used to oxidise 0·40% of silicon, and 0·05 cwt. of oxygen to oxidise 0·30% of manganese; assuming that the remanent oxygen is used to oxidise iron, then 7·1 cwt. of iron will be

oxidised, forming 9·1 cwt. of FeO. This makes a total weight of SiO_2, FeO and MnO of at least 10·0 cwt. This position is untenable :

(a) Because, from general considerations, this would be the dirtiest blow on record.

(b) Because the FeO/SiO_2 ratio does not even faintly resemble the ratio in the slags in Table V., unless it is also assumed that very heavy erosion of converter refractory takes place; we are told that this is not so, and if it were, the weight of refractory removed would be about 20 cwt. per heat and therefore not compatible with vessel lives of 200 heats, unpatched.

(c) Because the blowing loss would be at least 13%, assuming no mechanical loss by vomiting, &c., and this does not agree with the 5–6% quoted.

The only solution I can suggest to this apparent contradiction of facts, and I offer it with all deference, is this, that the true nitrogen contents were much lower than those reported in the gas analyses in Tables I. and II. If these percentages of nitrogen were obtained by difference, then the inference would be that the percentage of either carbon dioxide, free oxygen or carbon monoxide had been reported much too low. If it is the free oxygen or the carbon dioxide which has been reported too low, this would not vitiate the author's statement that carbon dioxide is the principal combustion product (as opposed to the formation of carbon monoxide).

If, however, it is the carbon monoxide percentage which has been underestimated, this would invalidate conclusion (c) on p. 342 P.

I have heard it suggested that part of the heat increment may be derived from the oxidation of iron to FeO; examination of Table IV. indicates a minimum of about 3·4 cwt. of slag, in which case, assuming that the ferrous and manganous oxides in the slag have been derived from the oxidation of the metal and that all carbon is converted to carbon dioxide, the carbon dioxide reaction is responsible for sixteen times as much of the heat increment as are the manganous and ferrous oxide reactions together.

In conclusion I should be pleased to hear Mr. Fassotte's views on the implication of the gas analyses.

Dr. W. R. MADDOCKS (The University, Sheffield) wrote : I have had the privilege of witnessing the process so admirably described by Mr. Fassotte in his paper. It is a process which is unique in so far as it has overcome the difficulties of the war-time supply of raw materials in a scientifically premeditated manner, which is to be highly commended.

The exceptional, though very successful, use of the cupola to produce high-carbon low-silicon iron from unselected low-carbon steel scrap is necessary to the success of the process.

The ultimate success of the process, however, depends on the initial temperature of the metal as charged into the converter. Whereas in the high-silicon-iron blow the temperature of the metal is increased by the combustion of silicon in the converter, in the low-silicon-iron blow the temperature of the metal is increased by the combustion of 80 lb. of fuel per ton in the rotary furnaces. If iron of a suitable silicon content were available, would this procedure be economical ?

The deductions drawn from the slag analyses of the high-silicon- and low-silicon-iron blows (Tables IV. and V.) given on p. 346 P are open to criticism. The slag in both the Bessemer blows is formed *ab initio* from the components of the slags, that is, FeO, MnO and SiO_2. The silicates

that will be subsequently formed from these components will depend on the temperature to which the slag can be heated. For example, the first slag formed from the components FeO, MnO and SiO_2 in a high-silicon-iron blow will be one which is liquid at the initial temperature of the metal, namely, 1280° C. This slag, given the time, will absorb SiO_2 until it is saturated at that temperature. The time necessary for such equilibrium to be established is never available in the Bessemer process. There will also be a temperature lag between the slag and the metal, which will in nearly every case be the hotter of the two. Contrary to the statement on p. 346 P that "there is a constant deficiency of SiO_2," ample SiO_2 is produced by the oxidation of the silicon of the charge. The SiO_2, however, cannot be taken into the slag until its temperature rises, when it will endeavour to establish its solubility equilibrium according to the constitutional diagram of the FeO-SiO_2 system (Fig. A). For the sake of simplicity the 3% of MnO in these slags has been neglected, although it is appreciated that it would lower the melting temperature of the slag noticeably.
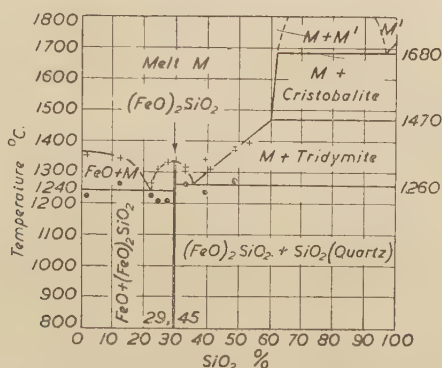
FIG. A.—Phase Diagram of the FeO–SiO₂ System (Herty, Fitterer and Greig, *Mining and Metallurgical Investigations Bulletin No. 36: American Journal of Science*, 1927, vol. 13, pp. 1–44, 133–154).

The slag of the analysis shown in Table IV. after 11 min. blowing must have a melting temperature less than that of the metal, *viz.*, 1310° C. Its composition conforms very nearly to the eutectic between fayalite and SiO_2 with a melting temperature of 1250° C. As the temperature of the bath increases, the slag is able to absorb more silica as shown in Table IV., the melting temperature of the slag increasing accordingly :

Time of blowing. Min.		11	18	28	37	Finish of blow.
Temp. of metal. ° C.	.	1310	1370	1560	1685	1690
Melting temp. of slag, approx. ° C.	.	1250	1300	1350	1425	>1500

The same argument applies to the slag analyses in Table V. Although the initial temperature of the metal is not given, it can be presumed to be of the order of 1450° C., since the slag formed after 2 min. blowing has an approximate melting temperature of 1350–1400° C. It would appear that the increase in temperature in the low-silicon iron was not great up to 8 min. blowing, but that later, up to 14 min. blowing, the temperature increment was sufficient to allow 60% of SiO_2 to be dissolved.

In fact, the slag composition, in the presence of excess FeO, is not a question of the availability of SiO_2, but is strictly dependent on the initial temperature of the blow and in accordance with the $FeO-MnO-SiO_2$ system.

The metallic loss will also be determined by the initial temperature of the metal in so far as the FeO content of slags from melts with a low initial temperature will be high. Since the FeO is produced by the oxidation of the charge, the more FeO stabilised in the slag the greater will be the metallic loss.

The corrosion of the converter linings can also be attributed, in part at least, to the difference in initial temperatures. Starting with a slag containing 54·5% of FeO (Table IV.) melting at a temperature of 1250° C., and finishing with one that contains 27·09% of FeO melting at temperatures in excess of 1500° C., this represents an increase in the silica content which cannot be supplied by the charge. The extra silica necessary will be taken from the linings in order to satisfy the physico-chemical conditions of Fig. A.

From an inspection of the compositions of the final slags in Tables IV. and V. a great difference in their viscosities would not be expected. It has been asserted, however, that the final slag of Table V. is less viscous than that in Table IV. A possible explanation of these facts would be that the slag in the Tropenas plant, owing to the long time of blowing (48 min.), had a greater opportunity of establishing an equilibrium according to Fig. A—that is, it would have attained a composition the melting temperature of which would approach the temperature of the metal and would thus be viscous. The final slag of the low-silicon-iron blow, on the other hand, owing to the short duration of the blow, would not have approached equilibrium for the particular temperature, in which case unfluxed SiO_2 would be expected in the slag. It should also be pointed out that the melting temperature of slags with more than 60% of SiO_2 increases rapidly.

Mr. S. R. ROBINSON (Ideal Foundry Division, Republic Steel Corporation, Newton Falls, Ohio, U.S.A.) wrote : This paper is of much interest to us as we operate a side-blown converter foundry for the production of steel castings for the Corporation plants.

We would inquire what is the minimum temperature necessary in the molten cupola iron entering the converter to produce steel of the proper temperature when using low-silicon metal ?

We understand that the rotary mixers are heated with powdered anthracite coal. Do the mixers have regenerators similar to those used on an open-hearth furnace ? We should appreciate it if the author would go into the details of the rotary mixers.

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AUTHOR'S REPLY.

MR. FASSOTTE wrote in reply : Mr. Townsend has recalled the circumstances that surrounded the origin of the process, which gives me an opportunity of expressing my thanks for the help in connection with the experimental work that I have received from a number of steel founders, and from Mr. Townsend in particular as he arranged in his works the first experiments which led to the confirmation of the theory on which the process is based.

Colonel Routledge is quite correct in stating that the economics of the process depend entirely on the relative prices of hematite pig iron and steel

scrap.   This applies, of course, to all steel-melting processes which can use both pig iron and scrap, but it becomes of vital importance in the case of the process entailing the use of scrap only.   When market conditions are such that it is cheaper to use the normal converter process, it is, of course, feasible to by-pass the rotary furnace and use the plant as a straightforward converter installation.

The remark of Colonel Routledge with regard to the incidence of the cost of the rotary linings is equally pertinent.   Unless a reasonable life can be expected from these linings, the process would not only be uneconomic but would also entail serious complications in production. Colonel Routledge has, however, established the fact that under certain market conditions the process can produce steel more cheaply than the normal cupola-cum-converter process.

As regards the question whether the process can be of value in an ordinary foundry as compared with a specialised wartime factory, I see no reason why a plant designed on a smaller scale than that operated by Colonel Routledge would not reproduce relatively the same economic features. It can be left to the steel founder to appreciate what value to put on increased production, larger number of heats in a given time, greater flexibility of output and consistency of iron analyses.

I agree with Mr. Spray's remark on this subject.   A steel-melting plant in a foundry is not put down in a haphazard manner; it is designed to fulfil a given programme, which takes into consideration the total requirements of steel in a given period, the frequency with which liquid steel must be available, the maximum size of individual pours, the handling facilities of the shops and a number of other factors.   It is when designing the plant to meet this programme that the designer has to decide whether he can justify increased capital expenditure in order to obtain greater flexibility.

The remarks of Mr. Spray regarding the effects of the sand addition should be read in conjunction with those of Dr. Cross.   It is correct to say that the results in various plants have been varying.   In cases where the sand additions have been judiciously made, the results have been worth-while.   The trouble caused by the building-up of the converter lining near the bottom is generally due to the use of an excessive quantity. The type of sand used has also proved to have its influence.

Dr. Whiteley's enquiry as to why the metallic loss should be less with low-silicon irons will find a partial answer in the analysis of the iron—a smaller amount of impurities having to be removed.   This, however, is not the full explanation, and the reduced blowing time is probably the principal determining factor of the reduced metallic loss.

Mr. Brown's assumption that a cupola iron devoid of silicon could not be blown satisfactorily is substantially correct.   After desulphurising, which can now be considered as a standard operation in any side-blown converter plant, the metal temperature is not sufficiently high for the carbon reaction to start, and the silicon combustion then becomes necessary to increase the temperature.   In experiment No. 1 on the second page of the paper, the iron temperature was probably in the neighbourhood of 1300° C. at the beginning of the blow, and when the bulk of the silicon and manganese had been removed this temperature had been increased to 1535° C., an increment of, say, 235° C.   The total increment expected in the converter is indeed of the order of 400° C. and both in the case of the normal converter and with the process outlined the final increment of temperature is obtained by the carbon reaction.   It is the initial kindling which is obtained in the one case by the combustion of silicon and in the

other by superheating. The actual temperature increase in the rotary furnace is between 150° and 200° C.

There is no theoretical objection to holding a charge in the rotary furnace overnight in order to make a flying start the following morning. Sufficient fuel would have to be burned in the rotary to offset radiation losses and there would be some extra labour for attending to the furnace during the night.

Answering Mr. Brown's question, all the temperature measurements were made by immersion pyrometer. In some cases, however, steel temperatures were taken in the converter itself and sometimes in the ladle, so that the temperatures are not strictly comparable.

I am in agreement with Dr. Cross on the difficulty of obtaining strictly reliable gas samples and of interpreting the results obtained. Dr. Cross has supplied the answer to Mr. Atkin. Primarily these gas analyses were intended to establish the proportions of CO and CO_2, and even though a doubt may exist as to the scientific accuracy of these figures, they seem to warrant at any rate the conclusion that we are essentially in the presence of a CO_2 reaction, which explains the heat increment.

Dr. Maddocks enquires whether the process would be economical if iron of suitable silicon content were available. It is entirely a question of relative prices of pig iron, ferro-silicon and steel scrap. With wartime market prices the process is cheaper than the normal side-blown practice. If the gap between pig-iron and scrap prices is sufficiently reduced, the advantage no longer exists, and it may become cheaper to use the ordinary procedure. I am indebted to Dr. Maddocks for correcting the statement that " there is a constant deficiency of SiO_2." Is he right, however, in assuming that the temperature of the slag is lower than that of the metal ? We know little about relative slag and metal temperatures in the various stages of the blow. If CO found in the bath burns to CO_2 at the surface, the slag may well be at a higher temperature than the metal in spite of the cooling effect of the blast, increasing correspondingly its avidity for SiO_2. Without the sand addition abnormally rapid lining wear has been noticed, and the practice of adding sand to the vessel has substantially contributed to make the process economically sound.

Replying to Mr. Robertson, the iron in the plant under review is charged into the converter at a temperature in the neighbourhood of 1450° C. and produces steel sufficiently hot to cast large areas of thin section (0·5 in.). To a higher temperature of the iron would correspond a higher temperature of the final steel.

The mixers have indeed regenerators enabling the combustion air to be heated to temperatures exceeding 400° C. The input of air and fuel is positively regulated to obtain high thermal efficiency and a controlled atmosphere in the furnace. Generally speaking, the mixers are built to a standard design, now well known and of which particulars have been forwarded to Mr. Robertson.

CONSIDERATIONS ON BLAST-FURNACE PRACTICE.*

By T. P. COLCLOUGH, D.Sc., M.Met., F.R.I.C. (London).

Summary.

Theoretical considerations and practical experience indicate that considerable economies in coke consumption may be effected in many blast-furnaces. To secure these economies it is necessary to attain a higher efficiency in the combustion of the carbon used within the furnace and to reduce as far as possible the weight of the slag-forming oxides charged in the burden.

It is highly desirable that a survey shall be made of British ores to determine the maximum size to be charged into the furnace on the basis of their thermal conductivities and permeabilities to gas penetration. The ores of high lime or silica content should be examined to determine their response to roasting and magnetic separation.

All British ores should be mixed, crushed and graded before being charged into the furnace, and all charging should be based on ore size and not quality of ore. All fines should be removed from the mixture and sintered before use in the furnace.

It is to be anticipated that with the correct preparation of the British ores, the reduction in coke consumption to be effected will be of the order of at least 20% as compared with common practice.

Introduction.

While the fundamental principles underlying the manufacture of pig iron in a blast-furnace are now well-established, the present trend of economic conditions makes it desirable to reconsider these principles in order to determine the policy to be adopted in present and post-war developments.

In blast-furnaces operating on low-grade British ores for the manufacture of basic iron for steelmaking, one of the most important factors, as regards both cost of materials and rate of production, is the coke consumption per ton of iron made. Current data show that this figure for furnaces operating on a burden of 100% British ores varies from 20–21 cwt., under the most favourable conditions, to over 30 cwt. per ton of iron under other conditions, with an average consumption of about 27 cwt. of coke.

The mere fact that such wide variations are found in current practice indicates clearly the necessity for a review of the methods employed, in order to secure more uniformity of performance and general improvement. These wide variations may arise from differences in the heat demand resulting from the use of different raw materials in the blast-furnace, or from a more efficient use of the coke in some furnaces than in others. A review of the factors involved has therefore been made to evaluate the effect of these different factors and to indicate the lines of action which will yield the maximum improvement.

Efficiency of Carbon in the Furnace.

The function of the coke charged into the blast-furnace may be summarised as follows :

(a) To provide the carbon absorbed by the metal.

(b) To reduce the oxides of iron and other elements to metal.

(c) To generate heat by oxidation of the carbon for the decomposition of the carbonates of lime and magnesia used for the formation of slag, and for other similar operations.

(d) To generate the heat required for the reduction of the oxides and the melting of the metal and slag, and the heat in the issuing blast-furnace gas.

For any given ore mixture and specified analysis of pig iron, items (a), (b) and (c) may be regarded as constant, but the quantity of carbon required to generate the heat for item (d) is capable of variation within wide limits, depending upon whether the carbon is oxidised to carbon monoxide or carbon dioxide. Since each pound of carbon oxidised to CO liberates only 4446 B.Th.U. as compared with 14,543 B.Th.U. liberated when oxidised to CO_2, it is evident that the degree of oxidation of the carbon is by far the most important factor in determining the carbon economy of the blast-furnace.

TABLE I.—*Total Heat Required for Reduction of Blast-Furnace Burden.*

Pig Iron Composition. %.						Weight of Each Element per Ton of Pig Iron. Lb.	Heat of Reduction from Natural Oxide. B.Th.U. $\times 10^3$.
Carbon	.	.	.	.	3·75	84·0	...
Silicon	.	.	.	.	0·50	11·2	141·1
Manganese	.	.	.	.	1·00	22·4	66·6
Phosphorus	.	.	.	.	1·20	26·9	285·3
Sulphur	.	.	.	.	0·05	1·1	...
Iron	.	.	.	.	93·50	2094·4	6785·9
Totals .	.	.	.	100·00	2240·0	7278·9
Net heat in liquid metal	.	.	.	.	.	.	1143·3
Total heat required per ton of iron		.	.	.	.	.	8422·2

As an illustration, consideration may be given to the theoretical carbon required for the production of one ton of liquid basic iron, neglecting for the moment the heat required for the formation of slag and the heat carried away by the gases. Table I. gives, for the specified analysis of pig iron, the weights of the various elements required, the heat of reduction from their oxides and the heat in the liquid metal—a total of $8·42 \times 10^6$ B.Th.U. per ton of metal. This heat must be generated by the oxidation of carbon by combination with the oxygen from the ore or from the air blast. Table II. gives the weight of carbon required to supply this heat, with variations in the proportion burnt to CO_2 and CO, while Fig. 1 shows both the weight of carbon required and the efficiency of the heat liberation. This graph shows that the carbon required falls rapidly as the proportion of carbon oxidised to CO_2 increases, and that the effective use of the carbon consumed increases from about 30% when all the carbon is oxidised to CO to 100% when the carbon is oxidised to CO_2. It follows from this that any steps taken to increase the ratio of CO_2 to CO in the gases formed by the oxidation of the carbon will result in a diminution of the carbon demand.

Unfortunately, there is a limit to the proportion of carbon or CO which can be oxidised to CO_2 in the presence of metallic iron, equilibrium being

established at a temperature of 680° C. with a gas mixture of 40% of CO_2 and 60% of CO. In practice it cannot be expected that equilibrium conditions will always be attainable, and for the purposes of discussion a ratio of 35% of CO_2 to 65% of CO has been adopted—this ratio being frequently observed in practice on furnaces in the U.S.A.

TABLE II.—*Relation Between Carbon Required and Proportion Oxidised to Carbon Monoxide.*

Carbon Oxidised to—		Carbon Required. Lb.
CO. %.	CO_2. %.	
100	0	1894
90	10	1544
80	20	1318
70	30	1127
60	40	993
40	60	802
20	80	672
0	100	579

It follows that the minimum carbon consumption to be anticipated in a blast-furnace will be attained when the ratio of CO_2 to CO in the gas arising from the carbon-oxygen reactions approximates to this 35/65 value.
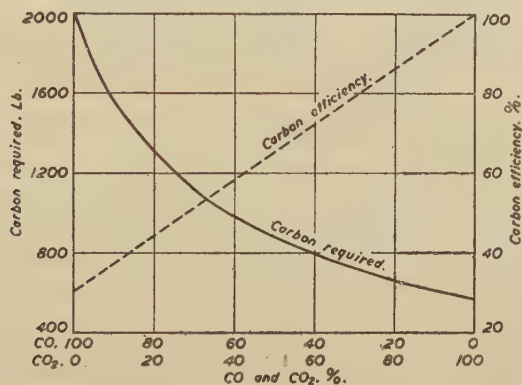
FIG. 1.—Relation between Carbon Consumption and Gas Analysis.

Conditions for Equilibrium.

In order to facilitate the attainment of gas equilibrium, three factors are of importance :

    (a) The heating of the ore.
    (b) Adequate contact between the ore and gas.
    (c) Uniformity of composition of the burden.

The first essential factor is that each piece of ore shall be heated, to its centre, to the temperature necessary for reduction, and that the ascending

carbon monoxide gas shall penetrate to the centre of the ore piece before the latter has travelled down the stack to a zone where the prevailing temperature is high enough to cause a reversion of the CO_2 to CO by reaction with incandescent coke.

The wider application of mechanical diggers for the winning of iron ore in recent years has had a marked detrimental effect on the operation of blast-furnaces, particularly where they are of small capacity.   With the large lumps of ore commonly shipped to the furnaces it is a physical impossibility for the necessary penetration of gas and heat to be attained in the time available in the furnace shaft.   It is self-evident that the smaller the piece of ore the greater is the surface area per unit weight, the better is the opportunity for the transmission of heat from gas to ore and the smaller is the distance of travel for both the gas and heat within the ore.   It follows therefore that there must be a maximum size of ore above which equilibrium conditions cannot be attained in the limited time available, and that all ore supplied to the furnace must be below this maximum size.

The second essential factor is that all parts of the burden in its passage down the furnace stack must be subjected to the free and uniform flow of the furnace gases.   To attain this condition the stock column must be reasonably free from channelling and size segregation.   With variations in resistance to gas flow in different parts of the cross-section of the stock column, it is inevitable that there will be preferential paths of gas flow, with resulting areas where the gas and heat transmission are insufficient to produce the necessary equilibrium conditions.   The inequalities of distribution arise, in the main, from variations of size in the pieces of ore, and to attain the desired uniformity of ore distribution and gas flow it is essential that the ore in each batch charged shall be of uniform size, within reasonable limits.   At this stage it should be pointed out that the fundamental factor in securing this uniformity of distribution and minimum resistance to gas flow is regularity in size and not the size itself, since both the gas resistance and the differential distribution arise solely from differences in the particle dimensions.

The third factor in securing equilibrium is to be found in the equalisation, over each part of the cross-sectional area of the furnace, of the physical and chemical energy required for the heating and reduction of the ore. It is evident that, if the amount of moisture and/or carbonates or the quality of the ore varies in different parts of the cross-sectional area, there will be differential demands for both heat and reducing gas.   In some parts the gas will be in excess of demand, whilst in others there will be a deficiency. To secure equilibrium conditions it is necessary to establish uniformity of composition in each batch of ore as it is charged.

It follows from these considerations that the blast-furnace can no longer be regarded merely as a piece of equipment for the smelting of masses of ore as delivered from the mine or quarry in any haphazard condition as to size, moisture content or quality, but that this raw material must be subjected to careful physical preparation before use.   In order to approach equilibrium conditions the ores must first be mixed together in the proportions necessary for the desired slag analysis, so as to obtain a reasonably uniform chemical composition.   This ore mixture must, if necessary, be crushed so that the maximum size of ore piece is less than that which can be heated and reduced by the furnace gases in the space and time available, and the crushed ore must then be screened, preferably into at least three sizes.   To secure uniformity of distribution in the blast-furnace, each size fraction must be charged separately.   The charging of the furnace must be by size and not by quality of ore, and the mixture of ores required for each charge must be made, not from the bins, as at present, but prior to stocking in the bins.

In practice, in order to avoid undue tightness in packing and excessive flue-dust losses, it is desirable that the smallest-size fraction shall not be charged into the furnace in this fine condition but shall be sintered in order to make it of more suitable size. The further benefit of this sintering treatment will be discussed later.

Application of Carbon-Efficiency Principles.

To illustrate the benefit to be anticipated from the application of this principle of carbon efficiency, an example may be taken from one of the leanest ore burdens in Great Britain. A typical average analysis of the ore mixture and the burden is given in Appendix I., Table VI. The coke consumption with this burden has averaged 3210 lb. (28·7 cwt.) per ton of iron, and the blast-furnace gas has averaged CO_2 9·3%, CO 30·0%, hydrogen 2·4% and nitrogen 58·3%; that is, the ratio of CO_2 to CO is only 35/113 as compared with the desired ratio of 35/65. This gas analysis indicates that the reactions of CO with iron oxide in the upper parts of the stack have not proceeded to the maximum possible stage, and that the pieces of ore charged are so large that they have travelled, before their complete reduction, to such a position that part of the CO_2 formed has been reduced to CO by incandescent coke with consequent loss of carbon.

What changes are to be anticipated from the preparation of the ore by crushing and grading in order to approach closely to the desired CO_2/CO ratio ? Details of the burden and heat balance for operation with ore as delivered and with ore crushed and graded are given in Appendices II. and III. These show that there will be no alteration in the quantity of ore required or of the heat required for the reduction of the ore and melting of the metal. There is a reduction of slag weight of about 100 lb., with a corresponding small reduction of limestone requirement and slag heat demand arising from the lower coke consumption, and it is reasonable to assume that with the lower gas volume the temperature of the issuing gases will be lower, say, 300° F. as compared with 400° F.

The total heat demand for metal and slag—$12·47 \times 10^6$ B.Th.U. per ton of iron with graded ores—is substantially the same as that with ores as at present received—$12·59 \times 10^6$ B.Th.U. On the other hand, with present practice giving a blast-furnace gas containing CO_2 and CO in the proportion of 35 to 113, the heat generated per pound of carbon oxidised is only 6065 B.Th.U. as compared with 7210 B.Th.U. per lb. of carbon to be realised with blast-furnace gas containing CO_2 and CO in the proportion of 35 to 65.

It is to be anticipated, therefore, that the coke consumption under equilibrium conditions will approximate to 2610 lb. as against 3210 lb., a saving of about 600 lb. per ton of iron, or 19%. This coke economy is based entirely upon the more efficient use of the coke.

The relation between the coke consumption and the proportions of CO and CO_2 in the blast-furnace gas made for this particular burden is shown in Fig. 2.

The first step to be taken to secure economy in coke consumption is, therefore, to mix the ores as thoroughly as possible, to crush the ores to a maximum size, to screen into suitable sizes (removing the fines) and to charge the different sizes in separate layers into the blast-furnace. It is desirable that exploratory work should be carried out on the various types of ore available, in order to determine the maximum size of ore piece to be charged and the grading of these ores, and thereby to establish the best conditions for uniform distribution and porosity.
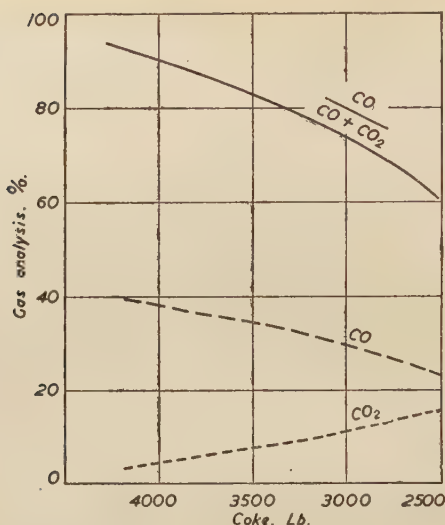
Fɪɢ. 2.—Relation between CO/CO_2 Ratio and Coke Consumption.

Reduction of Heat Requirement in the Blast-Furnace.

The details of the heat required for the two burdens using graded and crushed ore, shown in Table VIII. in Appendix III., are summarised in Table III. Examination of this summary for the crushed and graded

TABLE III.—*Analysis of Heat Requirement.*

	A. Raw Ore.	B. Crushed and Graded Ore.	C. Crushed Ore with 40% Sintered.
Metal.	B.Th.U. $\times 10^3$.	B.Th.U. $\times 10^3$.	B.Th.U. $\times 10^3$.
Reduction of Si, Mn, P . .	602·8	602·8	602·8
Reduction of Fe . . .	6,628·9	6,628·9	6,381·4
	7,231·7 = 39·1%	7,231·7 = 41·3%	6,984·2 = 44·6%
Decomposition of phosphate and FeCO₃	215·7 = 1·2%	215·7 = 1·2%	186·7 = 1·2%
Heat in metal	1,142·1 = 6·2%	1,142·1 = 6·5%	1,142·1 = 7·3%
Total for metal . . .	8,589·5 = 46·5%	8,589·5 = 49·0%	8,313·0 = 53·1%
Slag.			
Decomposition of carbonates .	1,645·3 = 8·9%	1,594·3 = 9·1%	1,080·2 = 7·0%
Heat in slag	2,358·4 = 12·7%	2,283·0 = 13·0%	2,289·8 = 14·6%
Total for slag	4,033·7 = 21·6%	3,877·3 = 22·1%	3,370·0 = 21·6%
Decomposition and evaporation of water in burden . . .	3,484·4 = 18·8%	3,259·4 = 18·6%	2,371·1 = 15·1%
Sensible heat of blast-furnace gas (dry)	1,490·5 = 8·0%	871·4 = 5·0%	744·6 = 4·75%
Radiation, &c.	942·7 = 5·3%	923·1 = 5·3%	854·8 = 5·55%
Total heat required per ton of metal	18,510·9 = 100·0%	17,520·7 = 100·0%	15,653·5 = 100·0%
Ratio of heat requirement . .	100	94·6	84·5
Coke consumption ratio . .	100	81·3	71·3

ore shows that little reduction can be anticipated in the heat required for the metal itself, because any reduction in the manganese or phosphorus content of the iron will be largely offset by the increase of carbon and silicon in commercial pig iron. The most obvious methods of attack are to decrease the relative proportions of the heat required for the slag and, in particular, for the removal of water.

Calcination of Ore.

The oldest and most widely practised method hitherto adopted towards this end has been the calcination of the ore. Whilst this procedure has the immediate and obvious advantage of effecting economies by the reduction in the weight of ore to be transported, it also has the indirect advantage of reducing the coke required for the smelting operation. The improvement due to the decrease of water content requires no comments, but attention should be directed to the double effect of the presence of carbonates in the ore burden. The carbonates not only require the combustion of coke to provide the heat required for their decomposition, but the CO_2 which is liberated requires an equivalent amount of carbon to be burnt to CO only, in order to establish the desired equilibrium ratio. In other words, any CO_2 present in the ore reduces the efficiency of the carbon consumed, and decomposition of the carbonates by precalcination of the ore is of both direct and indirect benefit to the carbon economy.

Unfortunately, this process introduces definite disadvantages by virtue of the fact that calcination inevitably increases the proportion of fines in the ore, especially if the calcine requires crushing, and unless these fines are removed and sintered before charging into the furnace, the difficulties due to increased flue-dust losses and greater irregularity of distribution tend to offset the advantages to be derived from calcination. In all cases where calcination is practised, the calcine should, therefore, be screened and the fines mixed with the raw-ore fines for sintering.

Sintering.

It has been pointed out above that for efficient operation of the furnace it is essential that the ore fines shall be screened out from the raw ore or calcine and sintered before charging into the furnace. In this process the slag-making constituents are increased slightly by the ash from the coke breeze used for combustion, but the effect of this on the furnace slag is offset by the smaller weight of ash resulting from the decrease in coke consumption in the blast-furnace.

The advantages to be derived from sintering may be summarised as follows : First, the ore fines are put into a form which facilitates uniformity of distribution in the charge. Secondly, practically the whole of the CO_2 and the water, existing both in combination and as moisture, are removed from that portion of the ore which is sintered. Thirdly, the iron oxide tends to change to Fe_3O_4, which has a lower heat of reduction than Fe_2O_3, and, finally (a factor which is of the utmost importance in certain ores), sintering effects a considerable reduction in the sulphur content of the ore, as opposed to calcination, which always increases the sulphur content.

From the above it follows that the maximum advantages to be derived from sintering, apart from those resulting from the improved physical condition of the ore, are to be expected when the ores are of the carbonate and/or high-sulphur type. It is well known that certain of the low-grade ores of Northamptonshire and Lincolnshire tend to be of both the carbonate and high-sulphur type as contrasted with the siliceous, low-sulphur, out-crop types, and these former ores, therefore, are susceptible to greater improvement by sintering than the latter.

To illustrate the benefits to be expected from the application of sintering, the ore burden previously considered may be studied.

Table VII., Appendix II., gives the materials charged into the furnace, the analysis of metal and slag, the weight of slag formed, the volume and composition of the blast-furnace gas and the coke consumption to be anticipated when 40% of the ore used is sintered and the conditions in the furnace are such as to give the desired equilibrium CO_2/CO ratio.   Table VIII., in Appendix III., gives the details of the heat balance, and Table III. furnishes the analysis of the heat requirement into the various sections of the operation.

Comparison of the data for the burden using graded ore and sinter with that using graded ore alone shows a small reduction in the heat required for the metal reduction and melting, a slight increase in that required for the melting of the slag, but a marked reduction in the heat required for the decomposition of carbonates and for the evaporation and decomposition of the water in the burden ($4·85 \times 10^6$ B.Th.U. with the graded ores as compared with $3·45 \times 10^6$ B.Th.U. for graded ores and sinter).

As a result of this reduced heat requirement it is to be anticipated that the coke consumption with 40% of the ore sintered will fall to about 2290 lb. per ton of iron—a reduction of 320 lb. as compared with the graded ore burden, or 920 lb. as compared with the burden using raw ore.   With 80% of the ore sintered the coke consumption to be anticipated will be below 2000 lb., even with ore of this low iron content (24·8%, see Table VI.).

Whilst the above conclusions are derived from purely theoretical considerations based on average ore data, they furnish an illustration of the principles which have been the basis of certain developments in blast-furnace practice during the last ten years, and the suggested economies in coke consumption can be confirmed from practical experience.   The accumulated data derived from the modern plants installed during the last ten years point clearly to the necessity for the adequate preparation of the ore before it is used in the blast-furnace, and the economies to be effected as the result of such treatment are of such importance as to demand immediate steps for the general adoption of this method of manufacture.

Effect of Slag Volume on Coke Consumption.

The important bearing of the slag volume has been fully recognised in evaluating various types of ore, but it may be of advantage to review the weight of carbon or coke required per 1000 lb. of slag made in the blast-furnace.

A slag of the following ordinary type :

	SiO_2.	Al_2O_3.	CaO.	MgO.
Composition, %	30·4	18·0	42·6	5·0
Lb. per 1000 lb. of slag	304	180	426	50
(CaO/SiO_2 ratio 1·4)				

will require for its formation the decomposition of 760 lb. of $CaCO_3$ and 105 lb. of $MgCO_3$.

Using air blast at 900° F. and with the issuing blast-furnace gas at 400° F. the heat requirement per 1000 lb. of slag may be estimated at 355 lb. of coke (for details see Appendix IV., Table IX.).

Whilst in blast-furnaces operating on rich ores the slag volume is relatively small, and necessary to flux the sulphur content of the burden, in furnaces operating on low-grade British ores the slag volume becomes so large that its heat requirement represents a large proportion of the total heat, and leads to a correspondingly high coke consumption.   It is therefore

of importance to consider methods by which this slag volume can be reduced and their possible applications to current practice.

" *Acid* " *Burdening*.

The principles adopted in the so-called " acid " burdening process were two-fold : First, the mixing, crushing and grading of the ores as outlined above, and, secondly, the production of a slag with the minimum practical viscosity and melting point. It was found that these slag conditions were best fulfilled for slags with 22–26% of Al_2O_3 when the CaO/SiO_2 ratio was reduced from the normal 1·4 value to about 1·0. It was recognised that slags of such low CaO contents would have a reduced sulphur-carrying capacity and steps were taken to develop methods to desulphurise the liquid pig iron.

The reduction of the CaO/SiO_2 ratio from 1·4 to 1·0 carries with it a reduction of practically 30% in the weight of limestone required, and yields a lower weight of slag with the corresponding reduction in heat requirement for both these factors. Table IX., Appendix IV., gives a comparison between the limestone and heat requirements of the two methods of burdening for the same weight of silica, namely, 304 lb.

This calculation shows that while the weight of slag is reduced from 1000 to 870 lb. (13%), the coke requirement is reduced from 355 to 281 lb., a reduction of 20% in the coke consumed for slag-making purposes.

Whilst the benefits to be derived from the crushing and grading of the ores and the sintering of the fines, as outlined above, are of general application, it must be clearly understood that the benefits to be derived from the use of acid burdening are not of universal application. The economies so made arise primarily from the decreased weight of limestone required, and it will be evident that this method is applicable only so far as this weight of limestone can be reduced. In the case of limey ores, such as those of the Frodingham district, carrying an excess of CaO and requiring the addition of siliceous ore to give a correct burden, there is clearly little possibility of economy from the use of this principle.

Ore Beneficiation.

The most obvious way to reduce the slag volume formed by a particular ore mixture must involve the removal of some part of the slag-forming materials before charging the ore mixture into the blast-furnace. A number of processes have been devised for this purpose, particularly in other metal industries where the metal content of the ore is considerably lower than is normally found in the case of iron ores. The most commonly used methods are washing and magnetic separation. Both these methods are in use in cases where the impurities, chiefly silica, are not in combination with the iron oxide or in intimate physical admixture, or where the iron ore is of the magnetic type. In the U.S.A. a considerable tonnage of magnetic iron ore is being treated for the removal of silica. This silica is in such intimate mixture with the iron oxide that it is found necessary to crush the raw ore and separate into fractions by magnetic separation. The rejects are further crushed and again subjected to the separation process. The magnetic fines are sintered in the normal manner before transportation to the blast-furnaces. By this process magnetic ores varying from 25 to 60% in iron content are transformed into a sinter containing an average of 68·5% of iron with 2% of silica.

Unfortunately, the low-grade ores of Britain do not readily lend themselves to improvement by either of these processes. These British ores are non-magnetic and are not susceptible to magnetic separation. Attempts have been made in the past to remove a proportion of the silica and clay

associated with certain types of ore by washing, but little success was achieved. In these ores, particularly those of the chamosite type, the silica and clay are closely associated with the oxide of iron, and, as a result,

TABLE IV.—*Magnetic Roasting of Iron Ore.*

	Raw Ore.	Roasted Ore.	Magnetic Separation of 1000 kg.		
			Con-centrate.	Middlings.	Rejects.
A. *Siliceous Ore.*					
Weight :	1000 kg.	808 kg. 1000 kg.	684 kg.	88 kg.	228 kg.
Iron. %	28·0	34·7	43·9	20·4	12·7
Manganese. %	0·20	0·25	0·25	0·25	0·25
Sulphur. %	0·15	0·19	0·16	0·24	0·28
Phosphorus. %	0·54	0·63	0·65	0·60	0·60
SiO_2. %	26·9	33·3	23·1	52·1	56·6
Al_2O_3. %	6·77	8·38	8·4	6·6	9·1
CaO. %	4·04	5·00	3·4	6·8	9·1
MgO. %	2·61	3·20	2·3	3·9	5·5
Yield in magnetic separation :					
Iron. %			86·46	5·18	8·36
Sulphur. %			53·2	10·6	36·2
Phosphorus. %			69·4	8·2	22·4
SiO_2. %			47·4	13·8	38·8
Other slag-forming oxides. %			58·6	9·1	32·3
Slag oxides. Iron. % .	1·44		0·82	3·4	6·3
B. *Calcareous Ore.*					
Weight :	1000 kg.	759·5 kg. 1000 kg.	462 kg.	240 kg.	298 kg.
Iron. %	22·48	29·6	51·1	14·1	8·7
Manganese. %	0·15	0·20	...	...	...
Sulphur. %	0·41	0·54	0·32	0·83	0·64
Phosphorus. %	0·42	0·55	0·67	0·36	0·51
SiO_2. %	18·97	25·0	11·77	35·25	37·25
Al_2O_3. %	10·36	13·65			
CaO. %	11·49	15·19	} 16·8	42·35	47·94
MgO. %	1·92	2·53			
MnO. %	0·19	0·25			
Yield in magnetic separation :					
Iron. %			79·77	11·45	8·78
Sulphur. %			27·8	37·0	35·2
Phosphorus. %			57·0	15·6	27·4
SiO_2. %			21·76	33·84	44·4
Other slag-forming oxides. %			24·1	31·6	44·4
Slag oxides. Iron. % .	1·91		0·56	5·5	9·8

the tailings are normally too rich in iron to make the process economic. It is understood that recent experimental tests have demonstrated that certain classes of ore may yield an economic return for the washing operation, and further investigations in this direction are to be welcomed.

A third method is worthy of consideration.   Before the war, an attempt was made in Germany to establish on a large scale the manufacture of pig iron and steel based on the use of domestic ore.   These ores are low in iron content, averaging about 27% of iron, and are considerably higher in silica (averaging 25–30% of SiO_2) than the low-grade British ores.   Experimental tests were carried out with the object of removing some of this impurity with a view to reducing the slag volume and the coke consumption in the blast-furnace.   As a result of this experimental work it was decided to instal a plant for the treatment of one million tons of ore per annum as a first commercial unit.

TABLE V.—*Influence of Crushing Before Magnetic Separation.*
Iron in raw ore 30·64%; dry ore 32·6%; roasted ore 37·8%.

Size of Roasted Ore.	Magnetic Concentrate.		
	Weight. %.	Iron Content. %.	Iron Yield. %.
1 mm.	71·8	45·2	83·3
0·5 mm.	72·7	45·1	89·0
0·23 mm.	73·8	44·6	88·5

The process adopted was to crush the ore to a size of approximately 40 mm., to screen out all below 15 mm., to subject this small ore to a magnetic roasting and then to separate the gangue by electro-magnetic separation. The magnetic fines were then to be mixed with the remaining ore fines from the ore crushers and subjected to sintering in the usual manner.

The results obtained in trial tests (shown in Table IV.) indicate that both siliceous and calcareous low-grade ores are capable of considerable beneficiation by this process.   In general, the magnetic concentrate contains from 80 to 85% of the iron content of the original ore, but only about one-half of the slag-forming oxides.   The efficiency of the process depends upon the control of the temperature and atmosphere in the roasting kiln and the degree of fineness to which the roasted ore is crushed before being subjected to magnetic separation.   The influence of the crushing size on the yield from magnetic separation is indicated in Table V., which gives the results of a test carried out on a siliceous type of ore.

In the types of ore under consideration containing 20–30% of iron the removal of the slag-forming oxides effected by the process represents a reduction in the slag volume produced from the smelting of such ores of about 3000 lb. per ton of pig iron made; this corresponds to a reduction in coke consumption of about 1000 lb. per ton.

The results obtained by this treatment vary according to the type of ore, and it is not possible, with information so far available, to predict what will be the effect of this treatment on any particular ore.   It is considered advisable that a survey should be made of the various types of ore mined in Great Britain to determine the extent to which improvement can be effected, and also to examine the economic applications of the process.

APPENDIX I.—*Application of Carbon-Efficiency Principles— Ore Analysis.*

The analysis given below in Table VI. is for a lean-ore burden.   With this burden the ratio of CO_2 to CO is only 35/113 as compared with the desired ratio of 35/65.   That these conditions can be improved by crushing and grading the ore is shown in Appendices II. and III.

TABLE VI.—*Low-Grade Ore Mixture.*

	Composition. %.	Weight of Each Con-stituent. Lb. per Ton of Pig Iron.
Iron	24·83	2036
Manganese	0·24	19·6
Sulphur	0·024	1·97
Phosphorus	0·25	20·5
SiO_2	9·68	793·8
Al_2O_3	7·74	635·3
$3CaO.P_2O_5$	1·25	893·0 *
$CaCO_3$	18·25	
$MgCO_3$	1·45	119·0
$FeCO_3$	2·3	189·0
CO_2	9·65	791·7
Combined water	9·34	765
Moisture	15·9	1304

Charged :	
Coke	3210 lb.
Ore	8200 lb.
Limestone	460 lb.
Basic slag	240 lb.

* Weight of CaO only.

TABLE VII.—*Comparative Data of Burdens.*

	Raw Ore as at Present.	Ore Crushed and Graded.	Ore Crushed and Graded. 40% Sintered.
Raw ore. Lb.	8,200	8,220	4,932
Sinter. Lb.	...	...	2,160
Limestone. Lb.	460	390	395
Basic slag. Lb.	240	240	240
Coke. Lb.	3,210	2,610	2,290
Metal analysis	C, 3·8%; Si, 0·75%; Mn, 0·95%; S, 0·05%; P, 1·38%; Fe, 93·07%. (Same throughout.)		
Slag analysis :			
SiO_2. %	30·4	30·4	30·4
Al_2O_3. %	24·75	24·75	24·8
CaO. %	40·3	40·35	40·3
MgO. %	2·8	2·85	2·8
MnO. %	0·35	0·35	0·4
FeO. %	0·45	0·50	0·5
Sulphur. %	0·95	0·80	0·7
Slag weight. Lb.	3,140	3,040	3,040
Blast-furnace gas per ton of pig iron :			
Carbon dioxide. Cu. ft.	22,100 = 9·3%	27,000 = 13·8%	22,920 = 13·7%
Carbon monoxide. Cu. ft.	71,600 = 30·0%	50,100 = 25·6%	42,850 = 25·6%
Hydrogen. Cu. ft.	5,640 = 2·4%	4,900 = 2·5%	4,650 = 2·8%
Nitrogen. Cu. ft.	138,560 = 58·3%	113,670 = 58·1%	97,070 = 57·9%
Totals .	237,900	195,670	167,490

APPENDIX II.—*Application of Carbon-Efficiency Principles—Ore Grading and Sintering.*

The effects of ore crushing, grading and sintering on the coke consumption, slag analysis and blast-furnace-gas analysis are shown in Table VII.

APPENDIX III.—*Application of Carbon-Efficiency Principles—Heat Balance.*

Table VIII. gives figures for the heat balance when using raw ore, and then crushed, graded and sintered ore. (For a summary of Table VIII. *see* Table III.)

APPENDIX IV.—*Heat Requirement of Slag.*

Table IX. shows the relative heat requirements and resulting coke consumptions on normal and acid burdening, respectively.

APPENDIX V.—*Relation Between Size of Ore and Carbon for Reduction.*

To illustrate the effect of ore size on the weight of solid carbon consumed in the blast-furnace for the reduction of iron oxide and the reduction which can be effected by carbon monoxide gas, the pieces of ore may be assumed to be spherical. It is also assumed that the reactions occurring are :

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$$
$$Fe_2O_3 + 3C \rightarrow 2Fe + 3CO$$
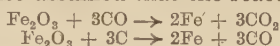
It has been suggested that the practical limit of carbon monoxide reduction is reached when the CO/CO_2 ratio is 65/35 and the temperature at the point of reaction between the iron oxide and the gas is 700° C.

The limit of carbon monoxide reduction will therefore be reached at the critical size of ore piece where the diameter is such that the heat transmitted from the surface, in the time available, raises the temperature of the centre of the sphere to 700° C., while the gas and coke surrounding the sphere is not over 900° C. With spheres of larger diameter the central core will be below this temperature until the piece of ore has reached a position in the furnace with a temperature of over 900° C. At this temperature any CO_2 possibly formed will be reduced back to CO by solid carbon, and, in effect, the reduction is at the expense of solid carbon.

With spheres of ore smaller than the critical diameter the whole of the reduction may be effected by carbon monoxide gas ; with spheres of greater diameter, a surface layer, equal in thickness to the critical radius, can be reduced by carbon monoxide gas to form CO_2, but the central core can only be reduced by solid carbon to form CO. The greater the diameter of the ore piece the larger the proportion which must be reduced by solid carbon, and, therefore, the higher the coke consumption. The weight of solid carbon consumed in the stack for reduction of the iron oxide must, therefore, be determined by the size of the ore piece relative to the critical diameter.

Fig. 3 shows these relative proportions in diagrammatic form, and also the relation between the size of the ore, the proportion of the oxide reducible by CO and the weight of carbon consumed to reduce iron from Fe_2O_3 with varying size of ore piece.

It should be specially noted that the relations between these factors are not linear, and that this fact furnishes a reason why the results obtained in certain installations are inferior to those anticipated. Rough crushing, yielding ore of a relatively large size, leads to a very small improvement in this reducibility factor and a correspondingly small reduction in the coke consumption. The possible economies only become really effective as the ore size approaches the critical diameter, the most marked reduction in carbon requirement occurring in the range between 3·0 and 1·0 times the critical diameter.

TABLE VIII.—*Comparative Heat Balances.*

	Heat of Reaction. B.Th.U. per Unit of Reactant.	Ores at Present Used.			Ores Crushed and Screened.			Graded Ores and 40% Sintered.		
		Quantity of Reactant.	B.Th.U.	%.	Quantity of Reactant.	B.Th.U.	%.	Quantity of Reactant.	B.Th.U.	%.
			Heat Required.							
Metal.										
Reduction of ore :										
Si	12,600	16·8 lb.	211,680	...	16·8 lb.	...	...	16·8 lb.	211,680	...
Mn	2,975	21·3 lb.	63,365	...	21·3 lb.	...	...	21·3 lb.	63,365	...
P	10,606	30·9 lb.	327,725	...	30·9 lb.	...	...	30·9 lb.	327,725	...
Fe as FeO	2,111	112 lb.	236,430	...	84·8 lb.	...	...	84·8 lb.	179,010	...
Fe as Fe_2O_3	3,240	1,973 lb.	6,392,520	...		...	...	1,181 lb.	3,826,440	...
Fe as Fe_3O_4	2,901	Nil	Nil	...		...	...	819 lb.	2,375,920	...
Total heat for ore			7,231,720	39·1		7,231,720	41·3		6,984,140	44·6
Decomposition of—										
Phosphate	925	154·5 lb.	142,910	0·77	154·5 lb.	142,910	0·8	154·5 lb.	149,910	0·9
$FeCO_3$	386	188·7 lb.	72,840	0·39	188·7 lb.	72,840	0·4	113·6 lb.	43,850	0·3
Sensible heat of metal less solution of 85 lb. of carbon	...	...	1,142,060	6·17	...	1,142,060	6·5	...	1,142,060	7·3
Total heat for metal	...	...	8,589,530	46·4		8,589,530	49·0		8,312,960	53·1
Slag.										
Decomposition of—										
$CaCO_3$	813	1,928 lb.	1,567,460	8·9	1,866 lb.	1,517,060	9·1	1,270 lb.	1,032,510	7·0
$MgCO_3$	628	124 lb.	77,870		123 lb.	77,240		76 lb.	47,730	
(CO_2 from all carbonates)		(8,494 cu. ft.)			(8,188 cu. ft.)			(5,300 cu. ft.)		
Heat in slag less heat of formation	...	...	2,358,360	12·7	...	2,283,050	13·0		2,289,780	14·6
Total heat for slag	...	...	4,003,690	21·6		3,877,350	22·1		3,370,020	21·6
Decomposition of water	6,787	150 lb.	1,018,100	18·8	150 lb.	1,018,100	18·6	150 lb.	1,018,100	15·1
Evaporation of water	1,240	1,989 lb.	2,466,360*		1,989 lb.	2,241,300†		1,200 lb.	1,353,000†	
Sensible heat of waste gases (dry)	...	...	1,490,500*	8·0	...	871,400†	5·0	...	744,600†	4·75
Balance. Radiation and other losses	...	...	942,700	5·1	...	923,020	5·3	...	854,820	5·55
TOTAL			18,510,900			17,520,700			15,653,500	

Heat Generated.

		lb.	B.Th.U.	lb.	B.Th.U.	lb.	B.Th.U.
Coke charged . . .		3,210 lb.		2,610 lb.		2,290 lb.	
Carbon at 87% in coke . .		2,793 lb.		2,270 lb.		1,992 lb.	
Carbon in metal . .		85 lb.		85 lb.		85 lb.	
Carbon oxidised . .		2,708 lb.		2,185 lb.		1,907 lb.	
			B.Th.U.		B.Th.U.		B.Th.U.
Tuyere carbon —→ CO .	4·446	2,332 lb.	10,368,000	1,974 lb.	8,776,400	1,685·5 lb.	7,493,700
Shaft carbon —→ CO₂ .	14·543	376 lb.	5,468,000	211 lb.	3,068,600	221·5 lb.	3,221,200
CO —→ CO₂ (in shaft) .	323	1,850 cu. ft.	597,500	12,124 cu. ft.	3,916,000	10,640 cu. ft.	3,436,700
Total heat from carbon .			16,433,500		15,761,000		14,151,600
Sensible heat in blast (900° F.) less decomposition of water vapour .			2,077,400		1,759,700		1,801,900
TOTAL .			18,510,900		17,520,700		15,953,500

* At 400° F.   † At 300° F.

TABLE IX.—*Heat Requirement of Blast-Furnace Slag.*

	Normal Burdening. CaO/SiO$_2$ Ratio, 1·4.	Acid Burdening. CaO/SiO$_2$ Ratio, 1·0.
Slag composition :		
SiO$_2$	$30·4\% = 304$ lb.	$34·94\% = 304$ lb.
Al$_2$O$_3$	$18·0\% = 180$ lb.	$20·8\% = 180$ lb.
CaO	$42·6\% = 426$ lb.	$34·94\% = 304$ lb.
MgO	$5·0\% = 50$ lb.	$5·0\% = 45$ lb.
Total weight of slag formed	1,000 lb.	870 lb.
CaCO$_3$ required	760 lb.	543 lb.
MgCO$_3$ required	105 lb.	92·4 lb.

Heat Requirement.

	B.Th.U.	B.Th.U.
Decomposition of carbonates	683,820	499,280
Sensible heat of CO$_2$ at 400° F.	27,650	20,430
Heat in slag at 900 B.Th.U. per lb.	900,000 (1000 lb.)	783,000 (870 lb.)
Total	1,611,470	1,302,710
Less heat of slag formation (SiO$_2$ + Al$_2$O$_3$ at 270 B.Th.U. per lb.)	130,680	130,680
Nett heat required	1,480,790	1,172,030

Heat Generated.

Calorific value of carbon with air at 900° F. and waste gas at 400° F. burnt to CO	4,793 B.Th.U. per lb.	
Carbon required	307·9 lb.	244·7 lb.
Coke at 87% carbon	355 lb.	281 lb.
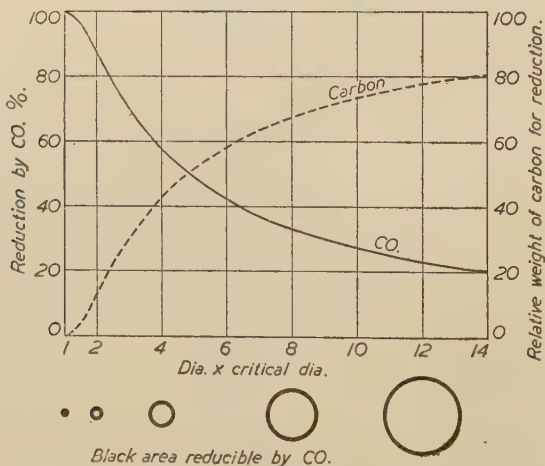
FIG. 3.—Relation between Size of Ore and Reduction by Carbon Monoxide.

Discussion on

BLAST-FURNACE OPERATION AND PROBLEMS.

The whole of the Autumn Meeting of the Iron and Steel Institute was devoted to a discussion on the operation of blast-furnaces and the problems encountered in practice; this was based on the following two papers:

" Ironmaking at the Appleby-Frodingham Works of The United Steel Companies, Limited." By G. D. ELLIOT and the Staffs of the Appleby-Frodingham Ironworks, Scunthorpe, and of the Central Research Department, Stocksbridge (The United Steel Companies, Ltd.). (*The Iron and Steel Institute*, 1944, *Special Report No.* 30).
" Considerations on Blast-Furnace Practice." By T. P. COL-CLOUGH, D.Sc., M.Met., F.R.I.C. (*Journal of the Iron and Steel Institute*, 1944, No. II., pp. 359 P–374 P (this volume).)

Four aspects were selected for consideration, and these were discussed as follows:

First Day.

   Morning Session.

   Fuel Consumption, based on:

   Dr. Colclough's paper : Relevant sections.
   Mr. Elliot's paper : Section IV., Blast-Furnace Coke.
   Section IX., The Utilisation of Fuel in the Blast-Furnace.

Afternoon Session.

Furnace Operation and Problems, based on:

   Mr. Elliot's paper : Section III., Furnace Plant De-sign and Layout.
   Section VII., Furnace Operation and Operating Problems.
   Section VIII., Scaffolds.
   Section X., Hearth Breakouts.

Second Day.

   Morning Session.

   Preparation of the Burden (with special reference to Ore Beneficiation and Sinter), based on:

   Dr. Colclough's paper : Relevant sections.
   Mr. Elliot's paper : Section II., The Blast-Furnace Burden.

   Refractories, based on:

   Mr. Elliot's paper : Section V., Blast-Furnace Re-fractories.
   Section VI., Hot-Blast Stove Refractories.

DISCUSSION.

(Figs. F to H = Plates XXVIII. and XXIX.)

INTRODUCTION.

(*First day, morning session.*)

The PRESIDENT (Mr. Arthur Dorman) : The real business of the Meeting is the discussion of these two papers on blast-furnace operation and problems, and they will be discussed together. I should like to express our thanks to the Directors of The United Steel Companies, Ltd., and to Mr. Baxter and Mr. Elliot for this wonderful production, Special Report No. 30, in which they record their experiences, their difficulties and their triumphs with equal candour, and which, I think, reflects great credit on them. I notice that in the Introduction they quote Mr. James Henderson as saying " There must be keenness to experiment and the courage to risk failure by trying something new." I think that this Report shows that that effort has been made, and that it has met with a considerable measure of success.

I also welcome Dr. Colclough's paper. After I had been elected President and read my Presidential Address, a few months ago, Dr. Colclough and I had a talk together, and we came to the conclusion that it would be a good thing if he would write a paper which would stimulate discussion. We did not know at that time that this Appleby-Frodingham Report was being compiled, but I think that the two papers go together, and I am sure that they will lead to a very useful discussion.

In the old days in Middlesbrough, which was the home of the iron-masters, I am told—it was almost before my day, which means that it was a long time ago—that if the price of coke was more than one-third of the market price of iron they put their furnaces out. That was a nice, easy way of doing it, but it does not get us very much further. I suggest that to-day high fuel costs may make possible things which up to now we have not considered feasible ; these papers give us some suggestions of how to counteract high fuel costs.

Mr. W. B. BAXTER (Director and General Manager, Appleby-Frodingham Steel Co., Ltd., Scunthorpe) : I feel that in introducing Special Report No. 30 it would be fitting for me to express on behalf of Mr. Elliot and all those who have collaborated with him in producing this Report the deep sense of loss that we feel at the passing of Dr. T. Swinden. Dr. Swinden throughout this work gave very freely not only of his great technical ability but also of that human sympathy without which many of our problems in research and in practice cannot be solved. He understood the difficulties, and he was an inspiration throughout the years that it took to compile the data in this Report.

I do not propose to say much about the Report itself—I can confidently leave that to Mr. Elliot—but perhaps I ought to say that the Report is an endeavour to set down in writing the actual experiences on a large ironmaking plant, and to set down with these experiences the opinions which have been formed and the beliefs which are held. Successes there have been and failures there have been. I suggest that in the great field of human endeavour, whilst we can learn something from success, we can learn a great deal more from failure. We have set down here, therefore, some of the failures that we have met with, knowing full well that if we learn the lesson of these failures we shall ultimately get on the road to success.

I know of no other operation of its kind in which so much difficulty

can be met with as in the manufacture of iron; and if there is anything in this Report which can help anyone in dealing with his own difficulties, I feel that it will not have been written in vain.

Mr. G. D. ELLIOT (Appleby-Frodingham Steel Co., Ltd., Scunthorpe) : Before I say anything about Special Report No. 30, I should like to say something about the people who have done the work and written the Report. As principal author, I feel in a very false position. This is the result of the work of many hundreds of people, from research chemists to laboratory boys, from the general manager to the lowest labourer on the ironworks and coke-making plant. The actual compilation of the figures and of the data presented was also done by many people. I hope that everybody who reads the Report will remember this. I have been very fortunate, in that I have worked with the finest set of men that one could wish for; they have helped, backed up, criticised and fought with me; other people than myself must take the credit, if any, for this Report.

We are of opinion that at Appleby-Frodingham the problem of iron-making is different from that in many other districts. Blast-furnacemen the world over have a tough job, but we think that at Appleby-Frodingham in many ways it is tougher than anywhere else. As a result of much discussion and work it was decided to set down for internal use most of this Report. We then thought that it might be of interest to other blast-furnacemen—I want to emphasise that we are thinking of other blast-furnacemen before anybody else—because we have found that the rest of the people in Great Britain who make a living out of pig iron are fumbling just as we are, that they have their theories and their ideas, and that they too are conscious of how little is known of the blast-furnace. It is in the hope of getting their experiences from our colleagues in the industry that we have presented ours.

I have said that at Appleby-Frodingham we think that ironmaking is difficult. It is difficult because of the ores that we use. I believe that I am right in saying that they are the lowest-grade ores used commercially in the world. In Section II. of the Report we show the need for treatment or preparation of the burden. We show how variable is the iron-stone, as it is delivered to the furnaces; it has been described without exaggeration as consisting of a mixture of monoliths and mud. We speak of our efforts to overcome the problem of variability. We write of sintering. We are producing up to 22,000 tons of sinter a week, and I am sure that any sinter man accustomed to turning out a product with 60% of iron would say that we are turning out 22,000 tons of very bad sinter, and I would agree with him; but we try to show you why it is bad sinter, and we describe some of the work that we are doing to make it better. When it is realised that 65% of our sinter may be described as impurities, it is difficult to see how with existing methods we can do better.

We also realise that a blast-furnace at Appleby-Frodingham is very like a blast-furnace in Brazil or anywhere else; but we think, rightly or wrongly, that the minor differences between a furnace in Brazil and a furnace in Scunthorpe are important, and we attempt to give our reasons for saying that.

I believe it was Abraham Darby—or was it Dud Dudley ?—who first complained to his coke-oven manager that his furnaces were suffering because of the coke, and furnacemen are still accused—and, we must admit, with some justice—that they do not know what they want in the way of coke. I suppose that the difficulty really lies in accurately assessing so many variables. In Section IV. of the Report Mr. Goodland and his staff have attacked the problem from what is, I think, a new angle. They have tackled it statistically, with some very interesting results.

As blast-furnacemen, we are not always satisfied with the coke that Mr. Goodland sends to us, but we are very satisfied that Mr. Goodland and his staff appreciate the importance of coke quality—that nebulous " something "—at the blast-furnace, and that the coke people realise that coppers saved in coke-making can easily be shillings lost in ironmaking. I suggest that if every coke-maker in Britain was as convinced of the importance of that nebulous " something," ironmaking would be much less difficult than it is to-day.

Some years ago we asked Dr. Chesters to investigate several of our problems concerning refractories. As he will be speaking on those Sections of the Report, I shall say nothing, except that we on the furnaces are very pleased that we have research workers as convinced as ourselves that there are still as many problems to solve as have been solved.

Referring to the Sections on refractories I should like to mention the development of carbon bricks, which I think is almost a classic example of what can be done by practical men and research workers, not only on the blast-furnace side but also on the brick-making side, when they work together to do something and not just to produce a report. I would emphasise that we produced the bricks before we produced a report on them.

It may be of interest to mention that breakout 22b, illustrated in Fig. 88, was the first instance of the use of carbon bricks. That particular furnace was blown-out last month and blown-in again yesterday, after being off for only 29 days. During that time the hearth was completely renewed without disturbing the bosh or stack. After blowing-out, the area of breakout was carefully examined and we found carbon bricks standing proud of the furnace wall by as much as 3 in. The major part of that breakout, which was a fairly big area, had been held by a $4\frac{1}{2}$-in. wall of carbon. In no place was there less than 3 in. remaining.

We speak also of the operation of furnaces. From blowing-in to blowing-out furnace operation is handicapped, because we do not know what is going on inside the furnace. We must be honest about that; we do not know what is happening inside a blast-furnace, and much of what we have written regarding the problems of operation may be described as thinking aloud. I hope that it will be read in that light. We realise that the results of our thinking may in many places be far from correct, but the results of our thinking are there for others to criticise.

We refer to the more serious troubles which can happen to a blast-furnace. When the first breakout occurred on a blast-furnace over which I had control, I felt ashamed of it; but when I went round and found that everybody else in the industry knew what a breakout was I was not so ashamed. I suggest that if we, as blast-furnacemen, are prepared to admit that a blast-furnace does get into trouble sometimes, and if we are prepared to speak openly of those troubles as well as of our record coke consumption for about three days (which we stretch to a month when describing it) we shall move further and faster than will otherwise be the case.

We had to tackle breakouts and we had to tackle scaffolds, and when we had to tackle scaffolds we had to start de novo. There was nothing to help us. There were only vague, general references in the literature. If we have done nothing else in this Report, we have given the poor man who meets a breakout or a scaffold for the first time some idea of how other people have dealt with those problems.

In Section IX., which was largely written by Mr. Bond, of our staff, we have set down our views on the use of coke in the furnace, and I think that the manner of doing so is in some ways novel. The last Section, Section XI., is, I feel, a very neat piece of work. It may say nothing which was not known before, but practical blast-furnacemen, research chemists, analytical chemists, refractory workers, X-ray workers and

metallurgists all collaborated in producing it. No one group of those men could have produced that Section with such convincing data, but several groups working together were able to tell the full story of what happened.

Such is Special Report No. 30. I hope that furnacemen—and again I emphasise that it was intended primarily for blast-furnacemen—may at least derive interest from it, as we have derived help and interest in compiling the data presented.

Dr. T. P. COLCLOUGH (London), introducing his own paper, said : Among the post-war problems with which the iron and steel industry will be faced, none will be of greater importance than the question of coke consumption in the blast-furnace. If Great Britain is to maintain its world position by virtue of its exports, secure full employment of its work-people, and have an economic production of pig iron, steps must be taken to reduce the amount of coke used per ton of pig iron made. In certain outstanding cases in this country the coke consumption compares favourably with any practice in the world, and the necessity now arises to place the whole of our pig-iron manufacture on the same basis.

The fundamental cause of the variation in coke consumption lies in the efficiency of the use of the coke within the furnace itself, and this is reflected in the composition of the blast-furnace gas. To secure lower coke consumption it is necessary that more of the coke shall be burnt to CO_2 and less to CO.

The paper indicates some of the practical methods by which this object can be attained. It is recommended that investigational work be put in hand immediately to determine the conductivity and reducibility of our iron ores, in order to define the maximum size of the material which shall be charged into the blast-furnace. All materials used in the burden should be crushed to below this maximum size.

It is recognised that one of the fundamentals of blast-furnace practice is to secure uniform distribution of the charge. For this purpose, the ore after crushing should be screened into two or three separate sizes and all fines removed. These fines should be mixed with flue-dust and sintered. The different sizes of ore and sinter should be charged into the furnace separately to give an open porous burden which will facilitate the ready reduction of the ore by the ascending CO gas.

The third factor for economic production is to secure uniformity of composition in the charge in all sections of the furnace, and for this purpose there must be adequate mixing of the ores before they are charged.

All the steps recommended are practical and have already been put into practice in some cases and have attained the benefits outlined. One of the first steps to be taken to secure the more economic use of coke is to apply these same principles in the preparation of the raw materials used to the whole of the blast-furnace industry. By the establishment of this procedure as standard practice it is visualised that a reduction of something like 20% in the coke consumption may be attained over a large part of the pig-iron production.

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FUEL CONSUMPTION.

(First day, morning session, continued.)

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Mr. G. H. JOHNSON (The Kettering Iron and Coal Co., Ltd., Kettering) : We have before us this morning two outstandingly interesting papers. which are, however, very diverse in character. Dr. Colclough gives us his considerations on blast-furnace practice, but unfortunately attempts to support some of his conclusions with certain thermochemical calcula-

tions which are hardly appropriate for the purpose for which he employs them. Nevertheless, I agree with his anticipation that with suitable preparation of British ironstone and burden enrichment a reduction in coke consumption of 20% may be achieved on the figure of 27 cwt. per ton of basic pig iron, which he alleges to be average practice at the present time. Indeed, in the Report sponsored by Mr. Elliot we are taken through the history of the accomplishment of an even greater economy.

As a purely war-time maker of basic iron at Kettering, in furnaces designed for foundry-iron production and using Northampton ironstone, requiring about 10 cwt. of limestone per ton of pig, with burdens containing from 50% to 100% of ironstone in the calcined state, with scrap additions which varied from time to time and using blast temperatures of 1500-1600° F., I have found a definite correlation between the iron content of the burden calculated back from the pig iron yield and the coke consumption. A 1% increase of iron content has resulted in an economy of 1 cwt. of coke as received, throughout a range from 27% to 34% of iron in the burden, corresponding to a coke consumption of 25·5 down to 18·5 cwt. based on coke as received, or 23·5 down to 17 cwt. on dry coke. The mean of over $4\frac{1}{2}$ years has been 21·23 cwt. of coke as received per ton of basic pig, equal to 19·55 cwt. of dry coke. This corresponds to a 20% economy on what Dr. Colclough has been pleased to call common practice. The CO/CO_2 ratio of the furnace gas was 3 : 1 on the average.

On p. 361 P of his paper Dr. Colclough takes for the purpose of discussion a ratio of 65% of CO to 35% of CO_2 (1·86 : 1) because this ratio has frequently been observed at furnaces in the United States of America. Such comparisons are misleading, because of the extreme difference between British and American blast-furnace materials. The paper by Wm. A. Haven [1] gives details of typical basic practice in five American districts. An average of these gives an iron content of the burden of 42%, as compared with 27% calculated from the third column of Table VII. of the paper by Dr. Colclough. Add to this major difference the further effect of 27·1 cwt. of slag of 24·8% alumina content, as given by Dr. Colclough, and compare it with the American mean of 12·5 cwt. of low-melting-point slag containing 14% of alumina. It is surely obvious that the thermal and chemical duties are profoundly different, and that CO/CO_2 ratios can only be considered as the effect of practice and not as the starting point of considerations. Comparison of the 2 : 1 CO/CO_2 ratio, which is the average of these five American furnaces, with the much higher $2\frac{1}{2}-2\frac{3}{4}$: 1 ratio at Appleby-Frodingham illustrates this fundamental principle and also the caution which is needed in using heat balances for postulating any particular theory in the present state of our knowledge.

Whilst Dr. Colclough's carbon-efficiency principles are elementary and cannot be challenged, the carbon efficiency of a working blast-furnace is dominated by hearth heat requirements, which in Appleby-Frodingham practice with crushed and sintered ores result in the above-mentioned CO/CO_2 ratio in the top gas, notwithstanding a coke consumption on their latest furnaces of about 21 cwt. with lean ores.

Like Mr. Elliot, I have been unable to determine the coke requirement of increments of slag, but, taking the sum of the non-iron-bearing (i.e., slag-forming plus gas-forming) materials for a 27% iron-content burden as a datum, I have found that the removal of the first hundredweight of non-iron-bearing material per ton of iron from the burden effects an economy of 0·4 cwt. of coke as received. This coke economy progressively rises until the removal of the last hundredweight, to give a 34% iron burden, effects an economy of 0·63 cwt., whereas our coke/burden ratio by weight

[1] *Journal of The Iron and Steel Institute*, 1940, No. I., p. 405 P.

at 34% of iron is approximately 0.35. Thus, the coke economy per 1 cwt. of excess burden removed rises progressively during the range in which I have operated, i.e., from 27% to 34% iron content. This is due to the increasing proportion of the excess material which passes to the slag, as distinct from the gas, as burdens become richer owing to the removal of moisture, carbonates, &c. Day-to-day observations plus the broader period indications with the ore charge varying from 50% to 100% in the calcined state, neglecting scrap additions, have given me a strong conviction that the coke requirement per ton of moisture in our burden is in the region of 10 cwt.

With easily reduced Northampton ore, coke economy can be obtained only by utilising a high degree of indirect reduction, and I am of opinion that the practical effect of moisture with such ore is to steepen the slope of the temperature gradients at the top of the stock column, so reducing the depth of the zone of indirect reduction. This prevents the attainment of an optimum CO/CO_2 ratio. Furthermore, I believe that while the moisture is being driven off reduction is inhibited to a large degree, particularly at fast rates of stock descent. These factors may explain the difference between the theoretical calculated effect of moisture and the important benefits accruing from drying, as reported by Mr. Elliot.

In order to achieve maximum fuel economy in a blast-furnace, as in any thermal apparatus, the positive and simplest way is to reduce the thermal work that has to be done. This means ceasing the present practice in certain cases of charging into blast-furnaces raw home ironstone containing large quantities of moisture, carbonates and similar gas-forming plus avoidable slag-forming material, and eliminating this previously by sizing and drying, calcining, sintering, &c., as may be most economical. One factor in the choice of the location of the preparation plant is the distance from the quarry to the furnace plant. Treatment should follow improved technique at the source of the ironstone, especially at some of the opencast workings, and each case requires separate consideration on its merits. Suitable preparation of an economic minimum quantity of furnace materials does not of itself raise the issue of the size of the furnace unit. From this it must not be inferred that I am opposing large furnaces. It is my belief that where large furnaces are requisite and can be based on stable burdens they will be installed. Dispersal of plant and the using up of material arising out of war-time conditions will not need to be considered in the future. This morning, however, I must confine my remarks to fuel economy, and in this connection I suggest that some of the smaller furnaces would have made a far better showing during the war period than they have done if the material fed into them had received the same degree of preparation as that fed into the larger ones.

To sum up, if we size and prepare the burden and increase the iron content by the simplest and cheapest means appropriate—I wish to emphasise this word " appropriate," because there can be no standard method—coke economies of the order envisaged by Dr. Colclough and accomplished at Appleby-Frodingham can be obtained.

Finally, I should like to refer to the painstaking survey made by the Appleby-Frodingham staff in Section IV. (Blast-Furnace Coke) of their Report. On p. 101, under " Conclusion," after recounting their efforts to control variables they enjoin blast-furnace operators (to quote their own words) " to adopt the most suitable measures for making the best of the coke with which they are provided." Blast-furnace operators have always endeavoured to do that. In normal times one might have more to say on this Section, but, having regard to the present serious position in the coal-mining industry, arising out of which many of our coking plants hardly know where their next day's supply of coking smalls is

coming from, or whether they are going to get full supplies or any supplies at all, some of the technicians' problems tend to become unsolvable.

Mr. I. S. SCOTT-MAXWELL (Messrs. Colvilles, Ltd., Glasgow) : Both these papers are very interesting, and there is a great deal of material here which requires careful study. Mr. Elliot and his colleagues have shown an enquiring turn of mind which many plant staffs, including Clyde Iron Works, would do well to adopt. For a low coke consumption the first essential is to have a good coke, and I agree very much with Mr. Good-land when he says that there is no test for coke which shows a high correlation factor with furnace operation. That seems to me to be rather a serious reflection on our coke research organisations, that they have not achieved some further advance in this direction during the many years they have been at work.

The quality of coke is affected chiefly by blending, coal size, battery temperature and carbonising time. For the best furnace operation it is important that the quality, whatever it may be, should remain constant. We have found that coal size definitely has an effect on coke size. If the coal is not crushed to fully 75% below $\frac{1}{8}$ in. we get an increased amount of smalls, and, further, it can be shown that during the crushing process a certain amount of petrographic separation takes place which gives a higher ash content and lower caking index in the $+\frac{1}{4}$-in. size. We can, therefore, upgrade coal to a certain extent by scalping off the $+\frac{1}{4}$-in. size, but that has to be considered in relation to the economics of what to do with the $+\frac{1}{4}$-in. size when it has been taken out.

We also found in the blending process, what with the high rate of turnover of wagons and the insistent demand by the railway companies to get them emptied, and a greater number of coals than one normally uses, that the men on the plant were occasionally putting wagons of a particular coal into any bunker without much reference to which was the right bunker. That, naturally, upset the coke quality very much, so we interlocked electrically the wagon tippler with the belt tripper on the top of the bunkers; that interlock also indicates which wagon has been tipped into which bunker, and how many wagons have been tipped during any shift. It is all recorded on a chart. This greatly helps in keeping a constant quality of coke and has been a thorough success on our plant. We also control the quenching electrically in order to get the same amount of water at each quench, independent of any variation due to the operator.

To consider, now, the coke in the furnace, Mr. Elliot has been more fortunate than perhaps he realises in having to deal with the same types of ores, all of which are very well blended in the most modern plant in Britain. We have had a great number of ores and no blending plant. We are essentially a foreign-ore plant, but have operated for most of the war on Northampton ores, and it was far from easy to find how this should be done successfully. During this year we have had certain deliveries of foreign ores, but again of widely differing qualities.

During all the different changes on the plant there were two common-sense conditions for the best furnace operation which I always tried to keep before me :

(1) The time of travel of the burden from stock-line to tuyeres should be constant from day to day, at a minimum value and equal to the maximum time of reduction of the ores being smelted.

(2) All the materials in the furnace, or at least 60% of them, should reach the tuyeres in the same state of reduction.

It seems to me that if these two conditions are achieved (and to do so it is necessary to have essentially correct furnace lines, some crushing

and some screening) you will get maximum throughput (from stock-line to tuyeres in about $7\frac{1}{2}$ hr. on a furnace 65 ft. high), or, if you like, a high turnover, and the coke rate and costs will be a minimum for any given ore. It is also possible to run your furnace at the maximum blast temperature, because the heat zones will be kept at a minimum size and in the right place.

I assume that on all modern plants it is known that screening, bedding and grading of the ores is essential and obviously helps the coke consumption. If, further, we assume that the coke is reasonably good we still have to pay attention to what Dr. Colclough has spoken of, and charge by size. The size, however, must be related to the heat requirements of the ore, and also to the time of travel from the stock-line to the tuyeres. It seems to me that this is a most important factor, and I think that Dr. Colclough's suggestions are perfectly correct, but I would emphasise again that all kinds of up-to-date and somewhat luxurious auxiliary plant will not give results unless the furnace lines are essentially correct. It would also help if the coke were charged by size, and, whilst this will not reduce the coke consumption, it will give an overall higher yield of blast-furnace coke from the ovens. That is to say, one should screen at the ovens, screen at the furnaces, and charge back in layers separately the $1-\frac{1}{2}$-in. coke nuts.

As far as our own operation on Northampton ores is concerned, we used approximately 30% of sinter containing about 45% of iron made from Northampton fines, together with 60% of Northampton ore from some 25 different mines, about 50% of which was calcined. On two 18 ft. 3-in. hearth furnaces the average output for the whole of 1943 was 6000 tons per week. Included in that figure is about 400 tons of scrap, so that the output per furnace, less scrap, was 2,800 tons per week. The average coke consumption was 20 cwt., the CO/CO_2 ratio 2·35 and the slag bulk about 22–23 cwt., and the iron input, taking into consideration the extra limestone added owing to the siliceous nature of the ores, did not amount to more than 30–32%. We found it impossible, however, to make low-silicon iron. The average silicon in the iron was 1·4%, but I suggest that if we had had a bedding plant to prepare the widely fluctuating ores this point could have been corrected. We did screening and crushing to a certain extent, but it was never possible to get the lime/silica ratio correct at the right point inside the furnace, and quick throughputs did not help this condition. The sulphur in the iron was 0·08%, and operation on very acid slags was possible owing to the sulphur in the coke not exceeding 0·7%.

It may be of interest to mention that on foreign ores we have operated with CO/CO_2 ratios of 1·75, coke at $15\frac{1}{4}$ cwt. and slag at about 11 cwt. per ton of iron, and outputs from one 18 ft. 3-in. hearth furnace as high as 4300 tons per week, with the scrap charge at about 200 tons. I realise fully that on lean ores it is not possible to obtain such good figures, but I think something could be learned by a study of what has been done on a foreign-ore furnace operating on Northampton ores.

Much has been said about the carbon reaction inside the furnace and about the possible control of direct or indirect reduction. I do not think we can control these matters, and if the furnaces are operating smoothly and regularly, and as fast as possible, then there is nothing else to worry about. The ore needs to be in the furnace for a certain length of time. A certain amount of coke is required to provide the heat for smelting and making slag, and, as Dr. Colclough points out, there is a limit to the proportion of carbon or CO which can be oxidised to CO_2 in the presence of metallic iron. The furnace, after all, has to do all the work, and the auxiliaries, such as coke-ovens, ore beneficiation plant, McKee tops, &c., should all lead to this one object. After that, there is little one can do

except improve the coke quality and maintain all conditions as nearly constant as possible.

In conclusion, I should like to ask Mr. Elliot one or two questions. I find it a little difficult to extract figures from his Report showing exactly what the furnace outputs and coke consumptions have been. It seems to me, from making some calculations, that the best outputs were obtained in the early days of the plant, but that during the years 1941–1943 the outputs have been gradually falling. I am referring, of course, to Nos. 9 and 10 furnaces, and I should like him to comment on this. I should also like to know what figure he uses for the cubic feet of wind per pound of coke burnt. It would appear that he is driving on wind pressure and not on wind volume, and as it is difficult, if not impossible, to measure accurately the wind volume from a reciprocating blower, he, presumably, calculates it from an average figure of coke burnt. From this can he tell us what wind velocity he has had at the tuyeres, expressed as cubic feet of wind per square inch of tuyere area ?

Professor THOMAS TURNER (Hon. Vice-President, Leatherhead, Surrey) : It is interesting to remember that about a hundred years ago, when chemistry was beginning to be applied to iron manufacture, researches were conducted on the reactions of the blast-furnace and the coke consumption. Professor von Tunner, about 1860, published the results of experiments in which ore was placed in an iron box with perforations.[1] The box was attached to a chain and allowed to descend into a furnace. The time and the depth were noted, and then the box was drawn out and the materials were examined. One thing which emerged from these experiments was that the reduction takes place in a charcoal furnace at a considerably lower point in the furnace, with a large proportion of CO_2, and with less fuel than in a furnace using coke.

Some years passed, and then Sir Lowthian Bell, a Past-President of the Institute, using mainly Cleveland ores, produced a classical work which everyone who is interested in blast-furnace reactions and progress might very well read even now. We pass from that time to the present Report, which I think will stand out as a classic. Just as students are recommended to read Sir Lowthian Bell's book to glean the knowledge gained up to that point, so now this Report will be of very great value, resulting, as it does, from increased knowledge and from team work. We must remember, however, that it deals with a certain class of ore, one of the poorest ores in the world. In that respect it is not so very different from the Cleveland ore.

I do not think that in Great Britain we need concern ourselves very much with the reactions with the richest ores. In peace-time a certain amount of rich ore came from the North—a rich magnetic ore—and other, hematite, ore came from the Mediterranean seaboard and elsewhere ; but, broadly speaking, in Britain we have had, and shall have, to work on the poorer ores with a large amount of slag. This Report will be very valuable in the understanding of the proper working of such ores.

Mr. J. H. PATCHETT (Messrs. Dorman Long & Co., Ltd., Middlesbrough) : The physical side to blast-furnace operation and its effect on the obtaining of low fuel consumption is to-day being given great significance, and I think anyone who has been responsible for the operation of blast-furnaces will fully realise the importance of having the best conditions in the shaft of the furnace to obtain the maximum gas/solid contact and consequent low fuel consumption.

Reference has been made to the work of Sir Lowthian Bell and the

[1] *See* Percy, " Metallurgy of Iron," pp. 456. London, 1864 : John Murray.

results that he obtained, published in 1884.   The carbon-efficiency prin-
ciples enunciated by Dr. Colclough in his paper were clearly set down by
Bell.   His experiments, with furnaces of varying capacity in order to
obtain the maximum amount of carbon fully burnt to CO_2 before leaving
the furnace in the escaping gases, led to the conclusion that an increase
in furnace capacity up to a point and the consequent increase in the time
during which the gases were in contact with the solid material gave an
improved fuel consumption.

Many figures are given by Bell, and I quote the following as repre-
sentative of the practice on Cleveland ironstone burdens at that time :

Height of furnace	.	.	.	.	80 ft.
Capacity .	.	.	.	.	11,500 cu. ft.
Weekly make .	.	.	.	.	345 tons.
Coke consumption	.	.	.	.	22·3 cwt. per ton.
Ironstone .	.	.	.	.	48·8 cwt. per ton.
Limestone .	.	.	.	.	13·6 cwt. per ton.
Blast temperature	.	.	.	.	905° F.
CO/CO_2 ratio .	.	.	.	.	2·28 : 1

A CO/CO_2 ratio of 2 : 1 and coke consumptions of 20 cwt. per ton of
pig were obtained on furnaces working in the Cleveland district at that
time, but the above figures are fairly average.   Since the time when these
results were obtained the practice in the Cleveland district has developed
on the lines of increased hearth diameters with furnaces of increased
capacity, and the capacity of the stack has been kept large at a sacrifice
in bosh angle, which even to-day is less than that usually adopted at
other works, viz., 71–73°, in order to obtain the maximum carbon efficiency
in the furnace.   The good physical condition of the Cleveland ironstone
permitted this angle without causing irregular descent of the materials
in the lower part of the furnace.

There has, however, been a steady falling away from the good CO/CO_2
ratio to a figure of about 2·8 : 1, undoubtedly due to the lack of adequate
gas/solid contact in the furnace shaft.

It is now imperative that the position should be restored, and this
can only be done by preparation of the burden, i.e., crushing, grading and
sintering, and the use of more enriching ores.

The preparation of the burden is equivalent to increasing the capacity
of the furnace, which is the same principle that was applied sixty years ago.
It would appear to be slow progress.

The present price of coke makes it imperative that its consumption
must be reduced in the furnace if we are to continue to manufacture iron
and steel in competition with other countries.   With the high cost of
winning coal, there may be a tendency to avoid properly cleaning the
coal and so allowing the ash to rise.   This would be very poor economy,
whatever may be the final cost of the coal, and must be avoided.

Dr. STACEY G. WARD (University of Birmingham) : These papers will
act as a stimulus for research in coke properties and blast-furnace reactions.
The coke-oven manager and the blast-furnace manager are severely
handicapped, because, with the present state of knowledge, neither can
specify exactly all the properties required in an ideal coke for the blast-
furnace.   The statistical attempts to correlate known coke properties
with blast-furnace working, as recorded in Section IV. of the Report,
show that only in the case of the Haven index and of the bulk density
is there any significant correlation.   This leads to the suggestion that
there is some other property of coke, at present unknown, which deter-
mines its quality for ironmaking or which has an overriding influence on
other properties.   It also leads to the suggestion that the property sought

is one of the coke substance itself, connected with cell structure and cell-wall properties, of which reactivity is probably only a partial measure, especially if, as suggested on p. 127 of the Report, the property which causes variation in bulk density is independent of size. Until the unknown property is discovered and measured it will not be possible to obtain the correlations sought. A useful field of research is opened up by the observations in this Section of the Report.

I am not sure that the joint figures for the drive index—*i.e.*, the joint figures for furnaces Nos. 9 and 10—are quite fair either to the coke or to the furnaces, even if they do represent a " no complaint " figure. In certain weeks during 1942 there were no gas kicks, or only one or two, so that in 1942 the index is zero for 24 weeks in the year. If, instead of the joint figure, the drive index is taken as the number of gas kicks given by the better-driving furnace of the week, a correlation factor of $-0\cdot38$ is obtained for the Haven index instead of the $-0\cdot25$ obtained by the author for the joint figure. I mention this to demonstrate that the joint figure may well lead to a lower degree of correlation than is fair to any one factor, rather than to decry categorically the use of the joint figure, for it is obvious that driving is influenced by factors other than coke.

The results of the recoking tests and of the experiments on the influence of hydrogen on the rate of reduction of ores and sinter by blast-furnace gas indicate the desirability of ensuring a reasonable volatile-matter content of the coke, compatible with other significant properties. If the results of the recoking tests given in Table XXXVII. are used to calculate the percentage yields by weight of the gases evolved, it is found that the values obtained are from $0\cdot3\%$ to $8\cdot4\%$, as shown below :

								Coke No.:	2.	3.	4.
Volatile content by standard method. % . . .									0·82	0·59	1·56
Total weight-% of gases evolved during recoking tests at temperatures of—											
500° C.	.	.	.	.	.	.	.	.	1·0	0·3	1·1
750° C.	.	.	.	.	.	.	.	.	1·2	1·0	2·5
1000° C.	.	.	.	.	.	.	.	.	3·7	2·9	6·9
1250° C.	.	.	.	.	.	.	.	.	5·2	5·4	5·9
1550° C.	.	.	.	.	.	.	.	.	6·3	6·7	8·4

The losses of weight (*i.e.*, yield of gases) at 1000° C. for the cokes having a volatile content, as determined by the standard method, of $0\cdot82\%$, $0\cdot59\%$ and $1\cdot56\%$ are $3\cdot7\%$, $2\cdot9\%$ and $6\cdot9\%$, respectively. These are much higher figures than are to be expected at 1000° C. from a coke prepared in ovens with a flue temperature of 1250° C., and the CO/H_2 ratio is very much higher than in the gas evolved during the normal coking within the range 700–1000° C. In the case of coke No. 4, the weight of hydrogen present in the gases at 1250° C., including that present in the methane and hydrogen sulphide, amounts to nearly $0\cdot5\%$ by weight of the coke treated. Similarly, the total weight of oxygen present in the products from the same coke (*i.e.*, free oxygen and oxygen present in CO and CO_2) is about $2\cdot6\%$ by weight of the coke treated at 1250° C. and $3\cdot7\%$ at 1550° C. It is unlikely that coke prepared in ovens with flue temperatures of 1250° C. still contains $3\cdot5\%$ or more of organically combined oxygen, or even over $0\cdot5\%$ of hydrogen. Typical figures for such a coke would be well below $0\cdot5\%$ of hydrogen and probably below 1% of oxygen. Where, then, has the oxygen originated which gives rise to so much CO and CO_2 in the gases collected during recoking? It may have originated in the mineral matter of the coke, by reduction of metallic oxides by the carbon present—that seems to be the most reasonable explanation—or it may have originated—though this is not so likely—from the water-gas, formed during quenching, tightly sorbed by the cell

walls of the coke. In any case it seems unlikely that 8·6% by weight of gases evolved from coke No. 4 at 1550° C. is true residual volatile matter from the coke.

The beneficial influence of the presence of hydrogen in blast-furnace gas on the reduction of ores and sinter suggests that the natural moisture in the blast may be useful, in that it produces hydrogen near the tuyeres, even if it does so at the expense of coke consumption.

Section IX. of the Report gives a very concise and practical exposition of what is a very difficult problem, or rather series of problems, and shows, indirectly, that a simple consideration of heat requirements is insufficient to enable correct conclusions to be drawn concerning the coke requirements of a blast-furnace; that local conditions are first considerations; and that it would be dangerous to compare different practices involving different types of burden without first giving detailed consideration to the many local factors involved. From the point of view of a simple overall heat balance, including utilisation of the top gases, it can be shown that it is immaterial whether the reduction in the furnace is direct or indirect; but from the point of view of the blast-furnace considered as an isolated unit it is important that a correct balance between the proportions of direct and indirect reduction should be attained and preserved, bearing in mind the fact that carbon reduces iron ores about three times as fast as CO.

The factors which cause different coke consumptions per ton of pig from burden of essentially the same chemical composition are: (a) The degree to which reversible reactions involving iron oxides, carbon and carbon oxides can proceed in the desired directions. These are controlled by the time and opportunity of contact, by the reducibility of the ore, and, of course, by the individual reaction rates; (b) humidity of the blast; and (c) coke properties. These have been well discussed in both papers.

For a given burden the yields of iron and slag will be the same whatever the coke consumption, apart from the contributions to iron and slag from the mineral matter present in the coke. The gas yield will depend upon the coke consumption and on the time of and opportunities for contact between the furnace gases and the burden. Accordingly, to reduce the coke consumption the endeavour should be to use easily reducible ores and sinter and good coke, all of the right size and right size-distribution, so that a minimum of reducing power is lost as CO in the top gas, and so that a maximum rate of iron formation is achieved so as to reduce the loss of heat per ton of pig by radiation and in cooling water.

As Dr. Colclough points out, carbonates present in the burden account for a much larger proportion of the coke used than might appear at first glance. Published analyses do not show the exact proportion of carbonates present in the Appleby-Frodingham burden, but 10% or more by weight of the ores charged may well be as CO_2 in carbonates, leading to a loss of coke, with a burden of 66 cwt., of about (a) 2 cwt. for decomposing the carbonates (assuming that carbon is burned to a gas having a CO/CO_2 ratio of 3 : 1, and the carbonates are in the form $CaCO_3$), (b) 2 cwt. for providing heat for carbon solution (assuming a CO/CO_2 ratio of 3 : 1), and (c) 2 cwt. by actual solution. It should, therefore, be possible to introduce a considerable saving of coke in the blast-furnace by calcining carbonates and carbonate ores outside the blast-furnace, as is sometimes done. The disadvantages of calcination are said to outweigh the advantages. It would seem worth while, however, to seek to overcome the recorded disadvantages, for example, by agglomeration (not necessarily by sintering) of the fines produced by calcination.

Both papers refer to experiments on ore beneficiation; both indicate that attempts, so far, to upgrade the ores from the Frodingham and

Northampton beds by washing have met with little success. It does seem that as our knowledge of the principles involved in mineral dressing advances, investigations into the possibility of upgrading certain of these ores by physical and mechanical methods should continue.

Mr. T. Carruthers (Workington Iron and Steel Co., Ltd., Workington) : In considering the proposals put forward by Dr. Colclough, it should be remembered that fuel economy does not usually end with economy in the furnace. Besides coke-oven managers and blast-furnace managers, in an integrated steelworks the question interests other people, including the chief engineer.

I was so struck by certain of the figures given by Dr. Colclough that I made an analysis of them and their implications, and had our fuel engineer, Mr. Dallas, study them too. I refer particularly to the figures of coke economy. Dr. Colclough shows that by crushing and grading the ore coke economies of 600 lb. per ton of metal are possible in the furnace, whilst if 40% of the ore be sintered this saving in the furnace is increased to 920 lb. per ton. I assume that these are target figures and that, as is frequently the case, we must expect, for various reasons, to fall short of them in practice. The data on which the following comments are based are given in Table A.

Taking the first case (case A, Table A.), the coke consumption is 3,210 lb. per ton of iron. That figure will evoke some protest from the furnace manager, but such figures do result on occasion. Allowing for gas for the stoves and for steelworks metallurgical requirements, gas is available for the boilers equivalent to 13,050 lb. of steam per ton of iron. This figure includes 2,260 lb. of steam per ton of iron required for blowing the furnace, leaving 10,790 lb. available for use in the works. If this latter quantity is not available from blast-furnace gas it must be generated from some other fuel, because if this weight of steam is once available from blast-furnace gas it will be expected always to be available, no matter how the furnaces are working. If there is a hitch in the operation of the blast-furnaces, perhaps a temporary one, the deficiency of blast-furnace gas required to generate this weight of steam will have to be made up by the use of some other fuel.

Coming now to the second case (case B, Table A.), the gas available, according to Dr. Colclough's figures of gas volume and analysis, will be 8880 lb. per ton of iron. Because of the reduced blast requirements, due to lower coke consumption, the steam requirements of the blower will be reduced to 1855 lb. per ton of iron, so that the figure corresponding to the 13,050 lb. in the first case becomes 12,645 lb. per ton of metal, of which 10,790 lb. are still in demand by the other parts of the works. There is thus a deficiency of 3675 lb. per ton of iron. This has an equivalent coke value of 510 lb. In other words, to maintain the surplus steam available elsewhere in the works, fuel other than blast-furnace gas will have to be used at the boilers to the extent of 510 lb. per ton of iron. This, deducted from the target figure, leaves a net saving of 90 lb.

In the third case (case C, Table A.), where 40% of the ore is sintered, 660 lb. of coke, or its equivalent, will have to be used at the boilers, which means a nett saving of 260 lb. of coke per ton of iron after allowing for gas for sintering.

I regret having to put forward these figures, but I have so often met with cases where the expected promising results from proposals made have not fully materialised in practice, and I want to utter a word of warning that in this case we must be prepared for a certain amount of disappointment in the direction indicated.

We at Workington are going to put into practice certain modifications of Dr. Colclough's proposals, and we expect that the final economy will

TABLE A.—*Application of Dr. Colclough's Data to an Integrated Iron and Steel Works.*

	Source.	Case A. Raw Ore.	Case B. Ore Crushed and Graded.	Case C. Ore Crushed and Graded, 40% Sintered.
Coke per ton of iron. Lb.	Tables VII. and VIII.	3,210	2,610	2,290
Gas analyses :				
CO_2. %	Table VII.	9·3	13·8	13·7
CO. %	,,	30·0	25·6	25·6
H_2. %	,,	2·4	2·5	2·8
N_2. %	,,	58·3	58·1	57·9
Ratio CO_2/CO	Calculated	35 : 113	35 : 65	35 : 65
Calculated value of gas. B.Th.U. per cu. ft. gross	,,	110	96	97
Gas per ton of iron. Cu. ft.	Table VII.	237,900	195,670	167,490
Blast per ton of iron. Cu. ft. (no loss allowed for)	Calculated	175,000	143,500	122,200
Coke saving. Lb. gross	Calculated from Tables VII. and VIII.	...	600	920
Stove efficiency. %	Assumed for case A	85	82·8	80·5
Heat in blast per ton of iron. B.Th.U. (less decomposition of water vapour) .	Table VIII.	2,077,400	1,759,700	1,501,900
Gas required per ton of iron. Cu. ft.:				
Stoves	Calculated	22,250	22,200	19,250
Sinter plant	,,	...	...	1,540
Gas equivalent of power for sinter plant. Cu. ft.	,,	...	...	5,520
Gas for metallurgical work in steel-works. Cu. ft.	,,	12,740	14,600	14,400
Gas requirements, total. Cu. ft.	,,	34,990	36,800	40,710
Gas available for boilers. Cu. ft. per ton of iron	,,	202,910	158,870	126,780
Reduction in steam requirements of blower. Lb. per ton of iron	,,	...	405	680
*Total steam requirements per ton of iron. Lb.	,,	13,050	12,645	12,370
Steam from gas available for boilers. Lb.	,,	13,050	8,880	7,500
Steam deficiency. Lb.	,,	Nil	3,765	4,870
Coke equivalent of deficiency. Lb.	,,	Nil	510	660
Nett coke saving. Lb. per ton of iron	,,	...	90	260

These calculations are based on the assumption that no increase in output is permissible.

No allowance is made for reduction in power for furnace charging, for possible saving in gas-cleaning power costs, &c., nor for gas loss.

On the other hand, no allowance is made for power for crushing, grading, and the conveying and handling attendant thereto, or for slight drops in efficiencies of blowers on lighter load, and of boilers and metallurgical plant, due to lower calorific value of gas.

No account is taken of the coke-breeze requirements of the sintering process. Such requirements would be of the order of 22 lb. per ton of sinter, or in case C 21 lb. per ton of iron, and should be deducted from the net saving under this heading.

It is assumed that the blower is operated by high-pressure steam only, *i.e.*, no exhaust steam is available.

It is assumed (probably wrongly) that the gas volumes in Table VII. are at 32° F. and 29·92 mm. of mercury, dry, and the calculated values are worked out accordingly. This, however, will not make a very material difference to the nett savings.

* Case A gives 13,050 lb. of steam available and therefore (usually) required. This is reduced in cases B and C by the reduced requirements of the blower.

be even greater than the figures given, since it might be possible to use, say, only three furnaces instead of four, but economies in fuel alone cannot

be as great as those given in Dr. Colclough's paper when the blast-furnaces are part of an integrated steelworks where there is no blast-furnace gas blown to waste.

Mr. R. MATHER (Member of Council : Skinningrove Iron Co., Ltd.) : I should like to compliment Mr. Elliot and his colleagues on the fact that almost all the operating data given in their Report are extracted directly from their records and relate week by week or in comprehensive totals to periods of considerable and stated length. Figures for an individual day or week do not have much effect on the profit and loss account of a company at the end of the year. It is not unknown for furnaces to work for two or three days on a very attractive coke figure and for that figure to be quoted to convey the impression that that is normal practice. I always scrutinise every statement about works practice to see whether it represents the best day of the month or of the year or relates to what is being done week-in and we k-out. Information on operating practice is of little value unless we know the period to which the result applies.

I agree with Dr. Colclough that economy in coke consumption is of very great importance both to the industry and to the national economy. I hope that as a result of a decision taken at a meeting of the British Iron and Steel Federation yesterday we may be able to get more positive information and see how to set about the task of securing an improvement in average coke consumption in our ordinary daily practice in producing pig iron in this country. The position to-day in that respect is not satisfactory.

Mr. Patchett gave us certain figures extracted from the book written by Sir Lowthian Bell in 1884, showing a coke consumption of 22·3 cwt. per ton of pig iron at that distant date. That reminded me that only a year or two ago I happened accidentally to come across a brief summary of some of the old records of my own company, also dating from the 'eighties, which showed that at that time Cleveland foundry iron was being made at Skinningrove entirely from Cleveland ironstone week by week with coke consumptions varying between just under 20 cwt. and a little over 21 cwt. per ton. It is a reflection on us that in sixty years we have not gone forward in this matter of coke consumption. It must be remembered also that that was with a burden which was little more favourable than the prepared and improved burden as finally worked out by the methods described in the Report before us. We need to ask ourselves, as ironmakers, whether we have made the wonderful progress that the present mechanical age is supposed to represent. I believe that we can do better than we are doing now, and we must do it.

I have one or two questions to put to Dr. Colclough. Under the heading " Application of Carbon-Efficiency Principles " he refers to Appendices II. and III., showing the coke consumption and various other operating features on semi-prepared and prepared burdens. I should like to know whether those purport to be actual figures or are just calculated. I should like to think that they were reliable, actual figures, but a doubt arises in my mind, because on p. 366 P, referring, I gather, to much the same Tables, he talks about these conclusions being " derived from purely theoretical considerations."

Fig. 2 of his paper shows the relation between the CO/CO_2 ratio and the coke consumption, but stops short at the most interesting point. The author very rightly tells us that we ought to get to a coke consumption below 2500 lb. of coke per ton of iron, but he does not tell us what the CO/CO_2 ratio is. It looks from the trend of the curves as if it would come to a relation between the two which I think even he does not claim is likely to be realised. A really dependable curve within the area which

is practicable would be interesting. None of us is interested in more than 3000 lb. of coke to the ton of iron, but if the curve could be extended at the lower end, based on operating results, its value would be increased.

Mr. LESLIE F. WRIGHT (Hon. Member of Council; Messrs. Gjers, Mills & Co., Ltd., Middlesbrough) : I find myself in general agreement with some of the views put forward by Mr. Elliot, especially when he suggests that coke consumption may be governed by hearth heat requirements. Dr. Colclough, on the other hand, suggests that " the degree of oxidation of the carbon is by far the most important factor in determining the carbon economy of the furnace," and with that statement I entirely disagree. Based upon the total heat requirements to produce one ton of iron in Table 1. of his paper, Dr. Colclough calculates that 579 lb. of carbon would be required to supply that heat when fully burnt to carbon dioxide.

If the results of furnaces operating on rich ores using limestone or dolomite as flux are examined—including those given by Mr. Haven to this Institute in 1940, and referred to by Mr. Johnson in his opening remarks—it will be found that about 580 lb. of carbon as carbon dioxide per ton of pig iron are usually present in the gases, whereas in Appleby-Frodingham practice the figure is in excess of 700 lb., whilst in the three examples given by Dr. Colclough the figures are 704·6 lb., 855 lb. and 720 lb., respectively.

I suggest, therefore, that the moment a blast-furnace is required to use anything but absolutely pure iron oxide and pure carbon in the manufacture of iron containing nothing but carbon, then the carbon ratio of the exit gases is an effect, and not a cause, of changes in the fuel requirements. Reference to Appendix II. shows that as the coke consumption is progressively lowered the reduction in the volume of blast-furnace gas per ton of pig iron is due to the presence of lower volumes of carbon monoxide and nitrogen. Thus, whilst I agree with Dr. Colclough's remark that there may be a limit to the amount of carbon dioxide which can be produced per ton of pig iron, I suggest that there is no limit to the amount of carbon which can be burnt at the tuyeres of a furnace by hot blast in order to satisfy thermal demands made by other influences which may have no connection with the fundamental chemistry of the process. Amongst these may be mentioned inadequate heat absorption by descending materials due to improper sizing and bad gas/solid contact, as well as the thermal demands for the removal of impurities by slag formation, &c. Hence, changes in the exit gas ratios are generally due to wide variations in the amount of carbon monoxide in the gases per ton of pig, and not to violent fluctuations in the amount of carbon dioxide.

In Table VIII. of his paper Dr. Colclough gives the following information :

	Coke Carbon.	Tuyere Carbon.
Ores at present used	2793 lb. = 100·00	2332 lb. = 100·00
Ores crushed and screened . . .	2270 lb. = 81·27	1974 lb. = 84·65
Graded ores and 40% sintered . .	1992 lb. = 71·32	1685·5 lb. = 72·28

These ratios are in sufficiently close agreement to confirm an opinion which I have held for many years, that the main governing feature in fuel consumption is the amount of carbon which must be burnt at the tuyeres per ton of pig iron in order to satisfy all the thermal demands therein accumulated.

In 1937, owing to the non-arrival of normal ores on account of shipping delays, available ores in stock had to be used, which although crushed were known to be too large for their density. Although the carbon

dioxide per ton of pig iron remained constant, extra fuel was required, the utilisation of which can best be summarised as follows :

Production of slag and decomposition of water	.	.	.	12·05%
Sensible heat in exit gases	.	.	.	28·25%
Loss by radiation and unaccounted for	.	.	.	59·70%
			100·00%

I consider that the " heat unaccounted for " is due to the difference between the thermal requirements of the pure reactions upon which the calculations are based and those of the impure materials actually used, including the effects of incorrect preparation and bad heat absorption.

Correct material preparation must facilitate chemical reactions, because of the improved contact of the reacting bodies, but until the physical side of operation is placed upon a much better footing than is generally the case to-day, the chemical side of the process cannot be considered as its weakest feature.

Mr. C. H. RIGGS (Messrs. Dorman Long & Co., Ltd., Middlesbrough) : I should like to answer the question of what blast-furnace managers want in the way of coke. They want coke suitable for burning in blast-furnaces up to the standard of that in Sir Lowthian Bell's book of sixty years ago.

Dr. C. H. DESCH, F.R.S. (Vice-President : Messrs. Richard Thomas & Co., Ltd., London) : Going through statements about coke consumption and comparing together a number of different works, one is met by the difficulty that the figures are obviously not calculated on a uniform basis. Cannot we have some agreement as to the way in which coke consumption should be expressed ? It is not always stated whether it is calculated on dry coke or coke as received. We know that when the coke comes to some plants it is carefully screened, and those screenings are not taken into account in the calculation. Then there is the question of the allowance of carbon in flue-dust and so on. Without some uniformity, which I think should be reached by general agreement, it is very difficult to make a proper comparison between different works.

The PRESIDENT (Mr. Arthur Dorman) : I agree. That is a very important point.

Dr. H. L. SAUNDERS (Imperial College of Science and Technology, London) : The underlying thought behind all the discussion which has so far taken place is that of fuel economy. I think that there is need for a certain amount of caution in using the exit CO/CO_2 ratio as an efficiency index. We can have a high top CO_2 figure as the result of quite a number of factors, such, for instance, as the early decomposition of soft limestone, imperfectly calcined carbonate ores, and those ores which happen to be particularly good catalysts for carbon deposition. It can also arise as a result of unusual furnace lines, such as where the height of the stock column is large in relation to its cross-section, and also with low rates of driving. In both these latter cases the increase in the CO_2 content may be very largely the result of increased carbon deposition rather than any measure of increased reduction.

There are other difficulties also connected with this whole question. In those reactions in which CO_2 is involved in the furnace, one usually calculates on a constant nitrogen basis for their assessment, and, since, apart from gaseous reduction, they proceed with opposite pressure changes, the nitrogen/carbon ratio of the gases is changing, so that one reaction

can easily mask another. As yet we know only a little of what takes place inside the blast-furnace, and a little less as to the location of the various reactions. To give one example, we know that carbon solution takes place near the bosh and deposition higher up in the stack, but who can tell us how much carbon is in migration at any instant within that furnace? That can be determined only by gas sampling through the furnace walls while the burden is being deliberately upset by altering the coke/ore ratio. This first reaction is endothermic and the second exothermic, and therefore, apart from the question of heat transfer between the blast and solids, the relative location of these reactions is a very important factor in determining the temperature gradient.

I think that we need to know a great deal more about the control of carbon solution as well as carbon deposition, and this is one of the problems which we have put down for future examination when we rebuild our experimental furnace. Like so many other problems, this is one which cannot easily be tackled on a full-scale furnace, because of the upset to production and management.

Furnace Operations and Problems.

(First day, afternoon session.)

Mr. G. D. Elliot introduced this subject for discussion.

Mr. H. L. O'Connor (Messrs. Stewarts and Lloyds, Ltd., Corby): With regard to Section VII. of Mr. Elliot's Report, I agree with the method put forward for blowing-in, but I think that the speed is rather fast. I would rather be slightly fast than slow, but I go to a burden/coke ratio of 1·5–1·7 when the furnace is full, instead of the Appleby-Frodingham figure of 2 : 1; I then try to come down to about 4% of silicon in the iron, running down to about 2·5% for four or five casts. This practice I believe to be better than coming down right away, particularly when the usual need is to get into production quickly, and the time saving is generally at the expense of the drying-out period. Drying-out is not dealt with in this Section, but it would have been well worth inclusion.

I gather that the author avoids the use of wet Northampton ore and sinter in the early burdens, and, in fact, that he does not like Northampton ore at all. I can assure him that there would be no bad effects from that ore. I do not use sinter in the blow-in, my reason being that the irregular dust content makes it inadvisable. Chemically, sinter should present no trouble. I wonder whether Mr. Elliot avoids sinter for the same or any other reason.

With regard to what is said on p. 170 of the Report, 4 hr. appears to be too short a time before turning gas into the main. Hydrogen is stated to be the guide and gas engines the concern. I have no gas engines, but I take oxygen as my indicator and my timing is at least 12 hr. before I am confident that the oxygen content is fit to put the gas into the crude-gas main. Mr. Elliot uses no flux in the coke blank between the tuyeres and burden. I suggest the advantage of fluxing this coke ash and increasing the slag volume by the use of blast-furnace slag in order to dilute the alkalis and give a clean-working slag in the hearth to start off operations.

With Mr. Elliot, I have come to the conclusion that voidage in the furnace stock is a more important factor in correct blowing than tuyere size, and that a number of troubles arise through varying voidage with constant tuyere area. There is a prevalent practice of reducing a tuyere area to obtain penetration, and I was brought up on this idea, but I now think this wrong unless the areas of all tuyeres are brought down, for

decreasing one tuyere area must mean driving more air through the remaining larger tuyeres. I agree entirely with the insistence on symmetrical tuyering.

I can endorse the author's remarks on blast temperatures with the carbonate ores. The best work at Corby has been achieved on blast heats of 700–800° F. Above 900° F. blast pressures always rise, and we very soon have a sticking furnace.

Mr. Elliot's remarks on the results of using high percentages of sinter in the burden are very interesting. I have not experienced his troubles when using sinter up to 35%, and beyond this I have no experience, but I should not expect his results. Corby sinter is not quite the same material as the Appleby-Frodingham product, the Corby sinter being much lower in both CaO and SiO_2. I think that one can expect at least a 50% sulphur elimination in the process of manufacturing sinter, and this should reduce the total aggregate of sulphur to be dealt with. I believe, however, that the form of the residual sulphur in the sinter has much to do with Mr. Elliot's trouble, and this, I believe, is the subject of investigation. I would also suggest to him that the trouble he is experiencing with losses through the slag notch is rather an indication that he is on the way to the shoddy of which he speaks later, and is possibly brought about by the same relation, inasmuch as there are two materials of different refractoriness.

I have little to say on cast-house practice, except that I find the use of a foundation of rammed carbon in the runners very successful; in fact, this foundation has lasted throughout complete campaigns. Here, again, I have a different iron to deal with, and the advantage is with me.

Coming to p. 182, I thoroughly agree with Mr. Elliot that a furnace in an ideal state of efficiency, with a low-silicon iron for steelmaking purposes and on a low coke consumption, is in an ideal condition to start hanging. This is not stated in so many words in the Report, but it is to be deduced from the section devoted to stock descent. It is a common thought among furnacemen that with a correctly sized ore, a total elimination of fines and a first-class strong coke there would be no hanging as long as the furnace was given reasonable treatment. That would probably be true, too, if all the other variables, such as blast heat and temperature, regularity and pre-knowledge of materials analyses, blast moisture, resistance of brick linings and so on were all under perfect control. Some of these factors have come in for a successful measure of control, but until they are all controllable there will be degrees of irregular stock descent.

In the early part of the sub-section on stock distribution (p. 192) it is stated that "the influence of the stockline is felt right down to the tuyeres." If this be true of the soft carbonates of Lincolnshire and Northampton, which disintegrate early in the descent of the furnace, then it is a standard truth for all furnaces. I would suggest, however, that the reverse set of conditions is very important, whereby changes in the hearth and lower bosh walls result in interference with the stock descent and also with the distribution. These changes can be very rapid. I work on a siliceous slag with conditions favourable to free stock descent. I have found that changes in blast temperature, slag basicity or coke values alter the zone of fusion in the furnace. A change here results in slag being thrown up against the lower bosh walls and stock where it is viscous at the prevailing temperature. This holds stock and deflects the gas flow, and so starts trouble further up the walls. The conclusion here is that the utmost regularity of conditions must be maintained in the hearth to bring about an even stock descent.

This, of course, only completes the circle and leads back to all the variables mentioned which should come under full control. I only partly agree with Mr. Elliot's assertion that one cannot blow through a sticking

furnace on his ores. I find that there are three types of hanging, *see* Fig. A : (1) Where the furnace pressure moves up, taking about ¾ hr. to rise, say, 5 lb., being checked, and repeating the performance. This might be called blowing into pressure ; (2) where the furnace pressure goes straight up, say, 5 lb., gradually works down to nearly normal, has to be checked and repeats again. This can be called blowing through pressure ; and (3) where the furnace is on high pressure, is checked, and goes straight to high pressure and stays there until moved again. This is blowing against a packed stock.

These different types of hanging either arise from different causes or are possibly degrees of Mr. Elliot's theory of buoyancy and packing. However, I find that the different types require different treatment. When blowing into pressure the wind needs cutting. When blowing through pressure, a gentle increase of wind at the correct time can get the furnace driving. With the third type, constant high pressure, cut wind can relieve the pressure, but the prolonged nursing costs much production. A quicker method is to increase the blast heat, which will not relieve the pressure,
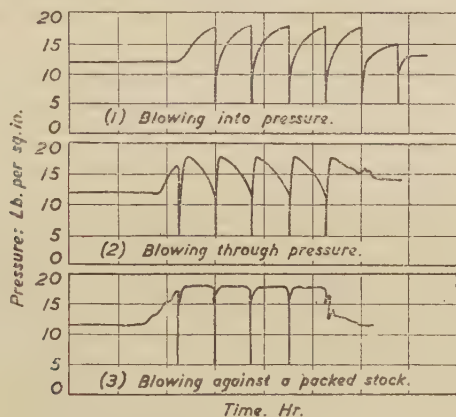
Fig. A.—Blast Pressure Variations during Three Types of Hanging.

introduce a coke blank and blow heavily to a slip. I have worked for many years on hard rich-ore oxides. Hanging with these ores was never a startlingly sudden affair, but more gradual, and generally led to a heavy slip. I did not experience the small " slip and build-up "—a " hotching " furnace, as it is sometimes termed. This seems peculiar to the soft carbonates.

On p. 191 Mr. Elliot takes up the question of shoddy. I think that all of us who have worked with carbonate ores have experienced it very badly in our time. My experience of it has been with irons containing about 1·1–1·2% of silicon rather than with those under 1%. I have not been able to go further than a generalisation that it appears to be caused by having materials of extreme refractoriness in the furnace together with materials easily reducible. I have been suspicious that the ore pits contain patches of this material, for a change of pits has often cleaned up the furnace. Also, when one furnace shows signs of shoddy the others generally do so too. The oldest furnace usually shows it first and worst. I find that a lowering of the silicon helps to clean up. I have moved in the direction of increasing the fluidity of the slag by the use of magnesia. This

has given excellent results and shoddy has been largely forgotten.   We have had about 12 months' experience of this.

On the question of stock distribution, I would particularly bring up the question of stock shields.   I am now awaiting the results of changes which I have made, and so cannot pronounce judgment, but I have come to the conclusion that the heavy-casting type, steel or iron, is no good, and also that grave dangers to the throat come from having armouring too low in the furnace.   I believe that the principle should be to use armour strong enough to resist the stock, and small enough so that failure of one piece does not affect a large area of brickwork.   The armour should be strictly limited to the area of its precise purpose, and the furnace should be prevented from operating at full blast on those occasions when the stockline is well below normal.   Many managers are loath to take the wind off because of the possibility of trouble elsewhere, but I believe that if the wind is kept on the furnace simply for that reason and the stockline gets well below normal, damage may be done to the stock shields equivalent to many months of furnace working.   I inspected the stock shields on the South Plant furnace at Appleby-Frodingham recently, and the condition of the armouring on the furnace taken out was the best that I have ever seen, which is to the credit of that type.

On p. 195 Mr. Elliot mentions trouble from sticky Northampton ore. With bell angles of 50° I get little trouble from sticky ore, and I am a little surprised that at Appleby-Frodingham there should be this trouble with bell angles of 53°.   A further point is that the distribution is unpredictable, and I would not argue against that.   What trouble there is, however, reflects back on ore screening, and the perfect screen for Northampton ore has yet to come.   I agree with Mr. Elliot that the stickiness of the ore has a profound effect on distribution, so much so that one is inclined to look for a more flexible distributor than the fixed automatic rotating type.   To look further ahead, however, it means retaining the fixed type of distribution as the better policy, and thoroughly preparing the materials.

Changing the charging to " coke first " has been tried a few times at Corby, but it has not given the marked effects which it has done at Appleby-Frodingham.   At Appleby-Frodingham they have certainly gone more deeply into the matter.   I have given furnaces 6- and 8-hourly periods of coke first for scouring purposes, sometimes with a marked effect and sometimes with no effect.   On the question of retaining inwall lines and its effect on distribution I would mention that when walls wear back beyond the nose of the horizontal stack plates the ladder effect on the furnace wall must be very harmful to stock descent.   I find that the insertion of alternate vertical cooling plates has kept the symmetry of the furnace, with much improvement in practice.

I particularly appreciate the note by Mr. Elliot at the end of this Section of the Report (p. 208).   The old blast-furnaceman was regarded as a strong labourer, but is now changing to a machine man.   His is a different type of work altogether, and the sooner this is recognised by training and choice of men the sooner will operation be smoother and more productive. One does not regret the passing of the hard work that the blast-furnaceman was called upon to do, but he must be fitted for the new phase, whereby production depends upon his intelligence rather than upon his muscles.

Mr. T. Powell (Messrs. Dorman Long & Co., Ltd., Middlesbrough) : From the Section on furnace operation and operating problems in this Report, it is easy to gather that a great deal of time and patience have been spent on finding a suitable charging sequence.   I think there is no doubt in the minds of furnacemen that this is a most important task, and every change possible should be tried until a satisfactory one is found.

During this war our practice was drastically altered, the quantity of foreign ores previously used being reduced almost to vanishing point. Northampton and Lincoln ores were substituted.   The slag made per ton of iron increased from 18 cwt. to 30 cwt., and the bulk ratio of ore to coke was 1 : 1·1.   The mechanically-charged furnaces were affected by this change much more than the hand-charged furnaces, and so particular attention was paid to the charging.   The high point in the rotating hopper was not very prominent.

A number of charging sequences were tried.   Briefly, these were as follows :

First Sequence :[1] C–C–dump–O–O, with a coke unit of 40 cwt. This gave a very brisk action at the tuyeres, with considerable top slipping due to carbon deposition, which was confirmed by the black colour of the exit gases.   These slips were as much as 8–10 ft., and checking beforehand to reduce their size was of no avail.   Naturally, flue-dust losses were high.

Second Sequence : C–O–dump–C–O, with a coke unit of 40 cwt. Within a week of this change the top slipping gave place to bottom slipping.   These slips were reduced to 2 ft.   The flue-dust losses were reduced by 30%.   As there was no appreciable reduction in the coke consumption, however, a third sequence was tried.

Third Sequence : C–C–C–C–dump–O–O–O–O, with a coke unit of 30 cwt.   This was not given a long trial, as the furnaces worked generally badly and the tuyere action became very sluggish.

Fourth Sequence : C–O–C–O–dump–C–O–C–O, with a coke unit of 30 cwt.   This was an improvement on the previous sequence, but the tuyere movement was poor and the coke consumption still unsatisfactory.

Fifth Sequence : C–C–O–O–dump–C–C–O–O, with a coke unit of 30 cwt.   This gave constant tuyere activity, with a slight tendency to top slipping.   The furnace worked freely, but the coke consumption was still on the high side.

Sixth Sequence : C–C–dump–O–O, with a coke unit of 30 cwt.   The effect of this change was soon observed.   A free-working furnace resulted, with flue-dust losses lower than ever before.   The coke consumption was considered normal, and the recording charts were a pleasure to look at.

This is referred to as a blast-furnace problem which takes time to solve, but, as Mr. Elliot says, " the solution of yesterday's problems may not be the solution of to-day's similar problems."   Many years ago it was most difficult to get an experienced blast-furnaceman to pass on his knowledge to others.   It is very different to-day.   The existing spirit of imparting information to one another, well to the front at the Blast-Furnace Conferences, must be maintained and even extended if this old country of ours is to hold its own in the future, and I know that our President has given every encouragement in this direction.

Dr. W. J. REES (Sheffield University) : I wish to say something on Section X. of Mr. Elliot's Report, dealing with hearth breakouts, and to offer some criticisms and suggestions.   I do so because I think that this Report will be a classic, and there are one or two statements in it which require some slight qualification.   I do not think that it is correct to say, as is stated on p. 233, that Germany has comparatively poor refractory clays.   Germany is in fact quite well off for very highly refractory clays in all the general classes of clay.   On p. 239 it is indicated that the degree

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[1] In these sequences, C stands for coke and O for ore.

of attack by CO varies with the amount of iron oxide in the brick.   It does not ; it varies with the amount of free iron oxide, and if the iron oxide is in combination the brick is fairly safe.

On Section X. as a whole my first reaction on reading it was to wonder which came first, the chicken or the egg.   Is the breakout primarily due to erosion or otherwise of the hearth or hearth wall, or have the conditions which might have conduced to the breakout been produced by some localised idiosyncracies in the cooling ?   I read through the paper again carefully, and came to the conclusion that the explanation given by the authors is satisfactory.   I for one would certainly accept the explanation which they build up of the real cause of the breakout at a particular furnace under the particular conditions at Appleby-Frodingham.

At the end of Section X. the authors make recommendations for the prevention of hearth breakouts, and this is the most important part of this Section of the Report.   With regard to paragraph (a), the permeability and porosity of the brickwork (p. 271), a tremendous amount of work has been done by the Blast-Furnace Refractories Joint Committee and then by its lineal descendant, the Blast-Furnace Refractories Panel.   The recommendations of those bodies are very much in line with the recommendations referred to in this paragraph (a), but on this particular point it has always puzzled me that ironmakers have not taken full advantage of the types of brick which have been available to them for years.

Before the war, it was possible to obtain in quantity bricks with zero permeability and zero porosity and a refractoriness of about 1800° C., and to obtain them in almost any desired shape and size, and well finished so that they could be built together.   I refer to the fusion-cast mullite refractory.   It is expensive, but other industries use it.   They find that it pays to use it because of its greater durability.   The fusion-cast refractory is perhaps used most largely in the glass industry, and the conditions in a modern glass tank furnace are not so very dissimilar to the conditions on the hearth of a blast-furnace, inasmuch as there are high-temperature erosion and corrosion to contend with.   I think that ironmakers might quite well investigate the possibility of using the fusion-cast refractory when it is available again, as I hope that it will be after the war, for these vulnerable parts of the furnace.

I am particularly interested in the recommendation with regard to the carbon brick, and I strongly support the view that it is likely that the carbon brick may be the answer to some of the difficulties of the hearth. My mind goes back a number of years to the time when I had to investigate the ill-fated Bassett process.   In the very-high-temperature rotary kilns which were used, the only refractory which would hold the superheated metal in the business part of the kiln was the carbon brick.   It had to be specially made, but it was a complete answer to the difficulties for that part of that direct process of steelmaking.

I have seen some of the carbon bricks which are being used in these particular furnaces.   They are very well made and are very highly resistant to erosion, and I think that they will be durable in service.   There is one point on which I should like some more information : What will be the effect of the very much higher thermal conductivity of the carbon brick on the behaviour of the lining and of the hearth as a whole ?   In one part of the Report reference is made to the infiltration of air into the outer part of the furnace lining.   With bricks of high thermal conductivity it is likely that the temperature of the back end of the bricks may be high enough, if air does infiltrate, for the brick to oxidise, and trouble to ensue.

Mr. JAMES DALE (Larkhall) : Regarding plant design and layout, I am sure that all who have been favoured in seeing the layout of the Nos.

9 and 10 blast-furnaces (South Works) feel that a good job has been done. In viewing the different furnace lines of the Appleby-Frodingham furnaces as shown on Plate IX., it is surprising to find such wide difference in the dimensions; for instance, we see 17-ft. stocklines incorporated in furnaces having hearth diameters of 11 ft. 6 in., 14 ft. 6 in., 15 ft. 6 in. and 17 ft., and heights varying from 70 ft. 5 in. to 83 ft. 7½ in., boshes varying from 19 ft. to 22 ft. 10½ in., bosh angles from 73° 12′ to 77° 30′, and with taper of stack from 0·402 in. to 0·102 in. per ft. It is assumed that all these furnaces, or those operating, are charged with prepared ore and a per-centage of sinter, but, unfortunately, owing to the large total coke consumption at these furnaces, it is obvious that many grades, of varying physical, chemical and combustible properties, are used which prevent an accurate assessment of the furnace lines and their efficiencies.

The various sizes of furnaces, differing so much in general dimensions, and with individual furnaces of such wide range in relative areas, must be productive of a wide range of efficiencies, if there is anything in furnace design at all.

The different methods of filling the furnaces—that is, by hand, bucket and double skip—must be productive of different results. It is interesting to note in Table LXXV., in which the characteristics of the North Plant furnaces Nos. 5, 6, 7, and 8 are given, that the hand-filled furnaces, which are of 14,000 cu. ft. working volume, are more efficient than the Pohlig-charged furnaces in fuel consumption, although the latter furnaces are of 20,000 cu. ft. working volume. This is possibly due to longer contact periods in the smaller furnaces, due to slower driving proportional to the working volume, or is it due to the better and more efficient distribution in the hand-filled furnaces ? It is probable that the contour of the materials lying on the bell, and consequently on the stockline, will be somewhat different from that of the Pohlig-charged furnaces. Does this account for the better fuel efficiency ?

It is possible that the materials as dumped on the bell of the hand-filled furnaces will be closer to the apex of the bell than that dumped from the buckets. To have the materials dumped close to the apex of the large bell was the object of decreasing the size of the small bell of the Algoma Steel Company's furnaces at Sault Ste. Marie, Canada, some years ago, which was productive of a considerable increase in tonnage and a much lessened coke consumption, with a longer life to the lining. Particulars of this are given in a recent issue of the *Journal of the West of Scotland Iron and Steel Institute*.[1]

There are very wide differences in hopper and lip-ring designs on the Appleby-Frodingham furnaces, all of which must have some effect on the stockline contour, and consequently on the gas flow.

Is it possible that improvement would follow on all bucket-filled furnaces if these were made higher and more narrow, following the lines of the McKee distributing hopper ? This should lessen segregation, and also permit the material to be placed nearer the apex of the large bell. The original Duquesne furnaces, those of the Youngstown Sheet and Tube Company, and also two furnaces of the Algoma Steel Company were bucket-charged, but in all these installations there were vast differences between the design of the buckets and those on the British blast-furnaces, the former being much higher and narrower than the latter. All these furnaces gave good performances, and it was probably only due to the introduction of the McKee distributor that bucket-charging was not more generally adopted in the United States of America.

In contrast with the other furnaces, we note the steep bell and hopper of Nos. 9 and 10 furnaces, free from any factor that would cause inter-

[1] 1933–34, vol. 51, Part IV., p. 68.

ference to flow, all with the object of attaining a fast speed of the materials sliding from the big bell, which is essential for good distribution. It is also noted that the small bell on the two furnaces is of such a size that the peak of the materials would be situated closer to the apex of the large bell. Mention is made of the preference for a large cylindrical section at the throat of the furnace. This is variable in practically all of the furnaces, this section below the working stockline being as follows, commencing with No. 1 : 9 ft. 11 in., 8 ft., 8 ft. 5 in., 8 ft. 7 in., 7 ft. 9 in., 7 ft. 9 in., 8 ft. 10½ in., and 9 ft. 6 in. In the case of the two large furnaces, Nos. 9 and 10, this dimension is 4 ft. 4 in. It is interesting to note that a very creditable coke rate was attained on the two large furnaces, which had the lowest straight section at the stockline. Truly, there are many advantages gained by these furnace lines and auxiliaries. The McKee top, the better coke from the local coke plant and the working volume of over 33,000 cu. ft. must have all contributed to this ; it is, of course, impossible to assess the part played by each of these factors in the excellent results obtained, but it does appear that the smaller cylindrical section was not harmful, particularly when the low flue-dust production is considered. This section is discussed in the West of Scotland Iron and Steel Institute *Journal* already referred to, and a rather different view of it is taken. Carbon deposition undoubtedly did take place in the poorly designed furnaces intended to handle large percentages of Mesabi ores, but I think that too much is made of carbon deposition in handling any English or foreign ores with which I have come in contact. Having been employed on American furnace plants at the period of the introduction of the high Mesabi ore consumptions when the furnace practice was so difficult, I feel that the extension of the straight section, which was introduced to lessen the troubles of carbon deposition, actually contributed to it. On many occasions while a furnace was hanging, the growth of the ores in the furnace, due to carbon deposition, amounted to as much as 3 ft., and often resulted in a heavy slip with a distinctly increasing explosive sound. The reduction of this straight throat section has, in my opinion, reduced the troubles due to carbon deposition, which are far more prevalent with the fine Mesabi ores than with any other ore. Carbon solution losses are of greater concern than carbon deposition, and are probably due to improper combustion. Efficient combustion and its location at the right elevation in the furnace, which are a feature of Dr. Colclough's paper, are deserving of prime attention and should result in real economies.

It would be interesting if the furnace lines shown on Plate IX. were dated, in order that the trend might be seen, also if operating statistics were given, with the wind blown, the tuyere area, the flue-dust production, &c. No doubt these have received the utmost consideration from the Appleby-Frodingham staff, as, to the best of my knowledge, the operating statistics for the Appleby-Frodingham plants are the best in the country.

In reviewing the campaigns of No. 4 blast-furnace, it is stated that this furnace worked very unsatisfactorily and produced excessive amounts of flue dust. This furnace was operated on several campaigns with only one gas off-take ; during the last relining, I understand, more logical gas off-takes were installed. I would like to ask if the furnace operation was improved.

It would be interesting to know if there is any relation between the section of the furnaces of various sizes and the wind to be blown for the most economical operation, also the speed of throughput for each furnace.

Mr. J. S. HOLLINGS, C.B.E. (Vice-President ; Messrs. Guest Keen Baldwins Iron and Steel Co., Ltd., Port Talbot) : I have had the privilege of visiting the Appleby-Frodingham plant, and whatever their difficulties

may be—and they have had them, and will continue to have them—they are to be congratulated on what they have done and on the example which they have set to the whole trade. Mr. Elliot remarked that they did not quite know what sort of coke they wanted. I should be interested to know whether he or any other blast-furnaceman in this room has come across a coke which was too hard for him. There has been a great deal of talk about reactivity, and from the point of view of domestic use I can understand it, but from the point of view of the blast-furnaceman I do not. If we ever do find a coke which is too hard, I think we shall have to get over the difficulty in the same way as with an ore, by crushing it down to a certain size.

With regard to carbon hearths, what I have to say is, I am afraid, rather ancient history, but many years ago I had to visit the works of the Lilleshall Iron Company. I found Mr. Rees—who has recently retired after being for very many years with that company—busy ramming the hearth with coke and tar. This was in 1902. I asked him why he was doing so, and he replied " This is the finest stuff I know to stop a breakout." At that time I was operating a small furnace, with an 8 ft. 6-in. dia. hearth, and was troubled with very frequent breakouts from the hearth. I was in the middle of those troubles when I went to Lilleshall, and when I came back I decided to try out what I had seen there. We got some ordinary $\frac{3}{8}$-in. boiler plate, 4 ft. 6 in. wide, which was the height of the cast-iron jacket, and we placed that in the form of a big strap round the furnace hearth 18 in. from the cast-iron casing. We rammed the intervening space with coke and tar. It was all done in the one shift. We put the wind on, and we never had another breakout.

I was so much struck by that that when I came to build a new furnace in 1908 I got my then chief to agree, much against his will, to put in a carbon hearth. We got it in the form of blocks from Germany. It cost a very large sum of money for a small furnace, but it did its job, and when we came to blow that furnace out five or six years afterwards, because the brickwork on the stockline had gone, the carbon hearth was still there, but not in such a form that we thought that we could build in on it again. Working it out, we did not find, though we had been free from trouble, that it had paid us ; and I was very interested just before the war to find that the Germans, with a view to cheapening the cost of carbon hearths, had very largely gone in for rammed coke and tar—not blocks but monobloc—carrying this to the top of the bosh, and that this was becoming quite a general practice.

I wondered how much further it was possible to carry this carbon lining than the mantle-plate, and, as we were about to reline a small furnace, I thought I would put in above the mantle-plate a panel of carbon brick, to see what occurred. It so happened that owing to shortage of ore we had to blow that furnace out after it had been running about 18 months, and I very quickly learned that from about 1 ft. above the mantle-plate the carbon panel had disappeared. That furnace was making hematite iron with easily reducible ore. Since then we have put a rammed-carbon hearth into that small furnace, and our refractory specialists and Major Frost, our blast-furnace manager, paid a great deal of detailed attention to it, and as far as I can tell made a first-rate job of it ; but I cannot give any information about it, because we have not had any ore to blow the furnace in on.

Mr. T. Hoskison (Round Oak Steel Works, Ltd., Brierley Hill) : The Report presented by Mr. Elliot and his colleagues is as complete a treatise on the blast-furnace practice in one district as has ever been given before this Institute. His language is trenchant and to the point, and I particu-

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larly like his remark that " no one man can live long enough to experience the full depths of depravity to which a furnace can sink." We are also grateful to Dr. Colclough for the way in which he has clarified our knowledge and put into simple language the scientific facts of ore reduction and carbon consumption.

Consideration of the two papers inevitably leads one to the conclusion that the remedy for the troubles associated with blast-furnace operation lies in two principal measures : The thorough preparation of the materials used and their proper distribution in the furnace. These, of course, are truisms which have long been agreed by blast-furnace operators ; the only difficulty lies in the means of attaining them. In this respect I think that some useful conclusions can be drawn from blast-furnace practice carried out in the manufacture of cold-blast pig iron. My friends in the blast-furnace industry are often inclined to be very scornful of such practice, owing to the small scale on which it is carried on ; nevertheless, it is true blast-furnace practice, as it reduces iron from its ores, makes pig iron, and fulfils the first purpose of all merchant pig-iron production, in that it makes a profit.

Mr. Elliot and his colleagues may be surprised to hear that this practice is carried on with an entire absence of all the troubles detailed by them in their Report. I can truthfully say that for a period of upwards of twenty years we have never had an instance of a furnace hanging or of a scaffold forming, of any irregularity of driving or of a furnace breakout. There are, of course, troubles of a different nature peculiar to the use of cold blast, but these are well understood and remedied as they arise.

The reasons for this immunity from the usual troubles affecting blast-furnace operations are, to my mind, wrapped up with the proper preparation of the materials and their distribution within the furnace. With regard to the preparation of the materials, I am quite convinced that in cold-blast practice we attain a far higher degree of preparation than that called for by Dr. Colclough in his paper. This preparation takes place within the blast-furnace by reason of the fact that the time interval between the putting of the ores into the furnace and the casting of the iron upon the pig beds is 40–45 hr. This allows that thorough penetration of the available heat units in the gas to the centre of the lumps of ore called for by Dr. Colclough, breaks up the ore and generally prepares it for complete reduction in the appropriate temperature zone.

Distribution is effected by hand-charging from small barrows into an open-topped furnace, without the intervention of a bell and hopper. This is, I consider, the most perfect method of distributing the materials in a blast-furnace. I well remember hearing of the difficulties which the Frodingham Company had in 1903 with their first mechanically charged furnace, in which the charging was done by bell and hopper. At the same time they had in operation open-topped furnaces, barrow-charged, working on the same materials, which were comparatively immune from trouble. I think that the Frodingham officials of that day will bear me out there, and that fact, together with the practice which we carry out in cold-blast pig-iron manufacture, points to distribution as the root of most of the troubles of blast-furnace operators.

The constant cry of blast-furnace operators is for some other method than the bell and hopper for charging the materials into the furnace. In the discussion of a paper read at the Autumn Meeting of the Institute in 1937 in Middlesbrough, time after time this plea was made. The bell-and-hopper method of charging materials into a blast-furnace has inherent faults which, in my opinion, can never be overcome, whatever attempts are made to side-step them by preparation of the materials and so on.

In this connection, three years ago I drew the attention of the technical

officers of the British Iron and Steel Federation to a new apparatus for charging the materials into a blast-furnace without hopper or bell, evolved by a mechanical engineer, Mr. W. A. Akhurst, who is here this afternoon. Dr. Saunders visited the Black Country and saw a model of the apparatus in action. This apparatus would put the material into the furnace in a homogeneous layer over the whole area of the stockline and thus, in my opinion, secure perfect gas/solid contact, with all its resulting benefits. On the other hand, if the blast-furnace operator desired to produce the V-shaped, inverted-V or M-shaped contour of stocklines he could do this quite readily by simple adjustments to the apparatus. I feel certain, from the model experiments which I have seen, that the apparatus will do all that is claimed for it, but whether it is an engineering proposition is for others to say.

I am sure that there are many brains exercising themselves at the present time on this problem of an alternative method of blast-furnace charging, and that when conditions again become normal we shall see developments which will result in perfecting blast-furnace charging, with the resultant elimination, in my opinion, of most of the troubles to which blast-furnaces are subject and with great economy in the coke consumption.

Mr. I. M. D. HALLIDAY (Central Research Department, The United Steel Companies, Ltd., Stocksbridge) : I should like to reply to the remarks made by Dr. Rees on Section X. of the Report, dealing with hearth break-outs. I am very glad, as I am sure Mr. Elliot is too, that he approves in general of the theory put forward about hearth breakouts. We also were worried to know whether the chicken came before the egg or the egg before the chicken so far as the effect of iron oxide in causing breakouts, or *vice versa*, was concerned. Actually we are quite clear now that it is iron oxide, FeO, which causes breakouts, and not breakouts which produce iron oxide in the brickwork. We are a great deal clearer on this point because of further work which we have done on examining the blown-out hearths of furnaces in the light of the theory put forward in Section X.

The main conclusion of Section X. is that, to prevent breakouts, we must prevent oxygen from entering the furnace hearth.

When we looked at the brickwork in the area of breakout No. 22b at No. 9 furnace, South Works, we saw that there were three main zones of brickwork. There was the unchanged brickwork at the bottom and to the outside, an intermediate zone which was much the same as the unchanged zone except in colour, being grey to mauvish-black, and a very narrow zone nearest to the point of breakout, which we called zone C and which was very badly changed. It was hard and slaggy, and, what was most interesting, it had metal in the pores. The metal was in every pore, the resulting porosity being in the region of 4–5%, or perhaps less. That was the first observation, that there was metal penetration for at least 1 in. in thickness into the working face of the hearth lining.

Fig. 91 shows that zone C is divided into at least four subsidiary zones ; these were examined in the laboratory. There is at least 40% of iron in the pores in zone C2 and another 30% in each of zones C3 and C4. On chemical analysis, one difference between these zones was the variation in the Fe_2O_3 content, which fell gradually in zones A and B but very rapidly in the zone C subsidiary zones from about 1·47% down to nil. More startling than that, in zone C2 there was a very high percentage of FeO. Fig. 93 is a graph of the variation of FeO and shows that FeO is exceedingly high in that zone, *i.e.*, 1 in. behind the working face of the brickwork. Table LXXXII. shows that in zone C1B, which is slaggy and on the outside of zone C, an excess of 11·72% of FeO cannot be accounted for on the basis of the oxygen required to give that percentage of FeO.

The final conclusion, therefore, was that we had to explain somehow the excess of oxygen required to produce the excess FeO. To do that we postulated that the atmosphere in the pores of the brickwork had a characteristic CO/CO_2 ratio which on the outer and cooler parts of the hearth was lower than in the inner or hotter parts of the hearth. In the hotter parts of the hearth, however, the CO/CO_2 ratio still had to be sufficiently low to oxidise the metal that entered the pores. To be low enough for this, we have to accept the idea that oxygen is coming in from the foundations—underneath the outside hearth jacket—up through the brickwork and oxidising the metal that penetrates the pores of the brickwork at the working face.

That essentially is the evidence. The reactions leading to a breakout could therefore be quite simply stated as (1) metal penetration into the brickwork; (2) progressive oxidation of the metal some few inches—perhaps 1 or 2 in.—behind the working face; (3) fusion of the zone of oxidised metal; and (4) removal of the working face by mechanical wear due to metal flow during the working of the hearth, because the brick is already slagged or cut parallel to the working contour of the hearth.

In passing, I may say that Mr. Elliot had given us the characteristics of breakouts gained by experience in running some ten furnaces over a large number of years. There were 22 breakouts in all, for which five characteristics could not be explained in themselves and could not be related to any point in furnace practice or in breakout experience; but on the basis of the theory which we developed it was possible to explain breakouts and the five characteristics quite easily. That explanation is given in Section X., and I shall not go into it further; but what I want to emphasise this afternoon is that we now have strong supporting evidence for this theory.

We examined No. 6 furnace at the North Works and found that the remaining brickwork of the hearth was made up of zones, *see* Fig. B. The FeO reduction zone was well defined and existed from the danger point where the lining is thinnest right down into the foundations. On the inside of the FeO reduction zone there was another zone in which the brickwork had hardly changed, except that the pores were filled with metal. Thus, right round the hearth we have the first characteristic, metal penetration through the pores of the brickwork. At a certain limit that metal is oxidised to FeO. Analysis of this zone showed that the FeO content was 13.35% in one section, and repeated tests gave a range of 13% to 17% of FeO at different parts. There was no iron on the outside of this zone. It is necessary to account for the oxygen required to give such contents of FeO.

We took samples of the brickwork on the inside, picked out the metal in the different zones and analysed it. We found that the metal was progressively oxidised. In the zone immediately on the inside of the FeO reduction zone the metal was low in manganese, in phosphorus and in carbon. In the FeO reduction zone the metal had as much as 9.9% of phosphorus. In the former zone the non-metallic portion contained 3.89% of MnO and in the FeO reduction zone 2.05% of P_2O_5. It will therefore be seen that, as the metal penetrates, the carbon and manganese are oxidised in the hotter zones, and in the final zone, at the limit of metal penetration, the iron is oxidised to FeO and the phosphorus to P_2O_5. This evidence is strong support to the theory.

To explain the FeO, &c., in the zones in question, Fig. 94 shows the way in which the oxygen can be accounted for, *i.e.*, by air coming in from the bottom and CO coming from the hearth. Incidentally, the porosity of the working face there is $4-5\%$, which would allow enough CO to come through the hearth from the inside.

One interesting point is the low fusion temperature of the FeO reduction

zone, which at 8 ft. 6 in. depth in the hearth is $2\frac{1}{2}$ in. broad at 6 in. in from the working face.   The melting point is as low as $1410°$ C., as against that of a working face, the grey zone, of $1670°$ C.   Those are figures for the non-metallic portions of the zones.

I should like to conclude with a few words on how to stop breakouts. We can improve the quality of the brick; we can cut down the permeability and porosity, and increase the alumina content.   Dr. Rees has advocated trying fusion-cast refractories.   We have not used these, but we are trying 73% alumina bricks.   These improvements, however, will not really solve the breakout problem.   It would be better to use carbon brick, because this material cannot be fused by FeO, if formed, and, secondly, carbon
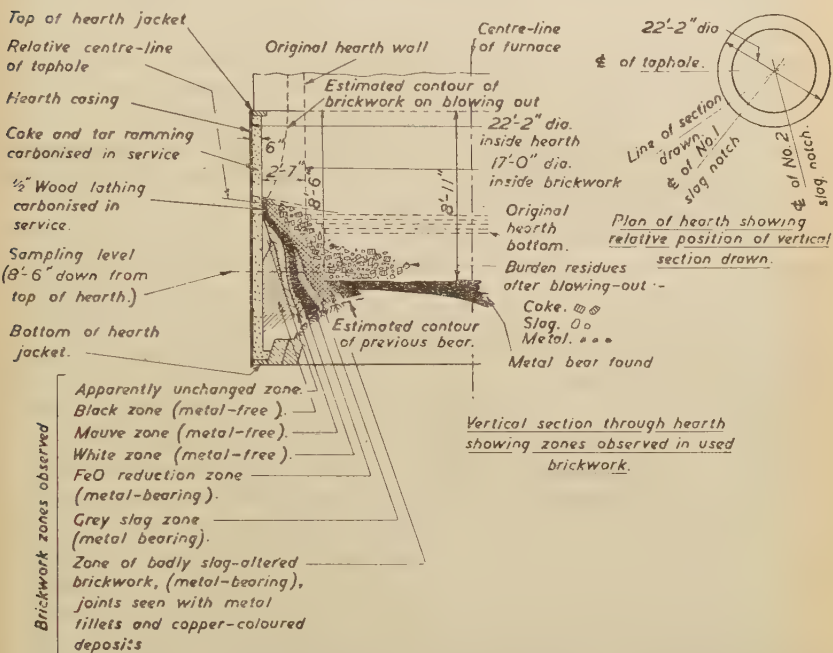
FIG. B.—Diagrammatic Section of Hearth Brickwork in No. 6 Blast-Furnace, North Works, Appleby-Frodingham, blown-out in December, 1942.

brick is not wetted by metal.   Metal will not penetrate the pores of carbon brick, so far as we can test.   What happens inside a blast-furnace may be unknown, but we would not expect penetration and oxidation of metal in a carbon hearth.   Metal might penetrate the open pores to a slight extent, but I think that the CO/CO_2 ratio would be high enough to prevent oxidation of the metal to FeO.   Carbon brick may not cut out the whole problem, because of possible burning of the carbon at the working face.   The real solution to the problem is to stop the oxygen getting to the hearth working face, and the only way to do that, as far as I can see, is to seal up the hearth somewhere in the foundations.   This is an engineering problem. However, we suggest a welded plate on the bottom of the hearth casing, deep in the foundations, to prevent oxygen, air, moisture, &c., from being drawn up.

Mr. T. CARRUTHERS (Workington Iron and Steel Co., Ltd., Workington) : As a furnace engineer, I want to thank Mr. Elliot for being so candid about breakouts. In my chequered career there have been a number of occasions on which breakouts have occurred, and they have more or less persisted, no matter what action was taken. We have gone in for stronger hearth jackets and better-made hearth jackets, for very elaborate water-cooling of the jackets either by external sprays or by internal staves of thick cast iron with circulating water-pipes cast in, and by exercising the greatest care in the selection of refractories, but breakouts have usually taken place, and it was too often the construction of the furnace which was said to be at fault.

These breakouts were undoubtedly due to erosion of the lining, and I formed the opinion that this erosion was due to the action of either the slag or the metal or the blast from the tuyeres or to combinations of these. I consider Mr. Elliot's remark that breakouts are the result of " a long-term cyclic process " very well chosen indeed, and with it I fully concur.

With that idea in mind, I have in recent furnaces endeavoured to make the length of the term of the cyclic process as long as possible. By this I mean that we have made the wall as thick as is reasonably permissible (4 ft. 2½ in. in the latest furnace) and of the highest alumina brick that we can procure. We have endeavoured to prevent or to reduce the action of the blast in causing erosion of this thick brick wall and, at the same time, to curtail the erosion that may be due to slag by employing two rows of close-spaced water-cooled copper plates below the tuyeres at or near the flushing-slag level, taking care to make the plates in one row completely overlap those in the other. Further, we have fitted inside the steel hearth jacket water-cooled staves of the most careful design, 6 in. thick, so as to have a big weight of cold casting to chill, or to attempt to chill, any liquid metal which penetrates the thick wall.

These precautions have met with success up to the present. One would think that water-cooling the jacket by sprays or internal staves, if well done, would be a certain preventative of breakouts, but that is not the case, as if enough liquid metal reaches the staves or jacket it comes through. This must be due to ordinary refractories being such poor conductors of heat that they prevent the cooling system from being effective.

Mr. Elliot's enterprise in adapting and developing the Continental practice of using carbon bricks for the hearth is very admirable, and we at Workington are paying it the sincerest compliment by using carbon bricks for the next reline. The bricks are actually being manufactured at present. The argument for their use is almost complete ; they should be inert to the action of both slag and metal, and their high conductivity should enable the water-cooling of the hearth to be much more effective.

When the carbon lining has proved as successful as I feel sure, and sincerely hope, that it will (and we have been told by Mr. Hollings that it has been a success in Great Britain), it will convince me that the theory that hearth breakouts are caused by infiltration of air, producing oxides of iron, which in turn destroy the refractory lining, may not be completely correct, because it is easy to imagine that infiltration air would do quite as much damage to an incandescent carbon hearth as it could possibly do to a firebrick hearth by the production of oxides of iron.

Dr. J. H. CHESTERS (Central Research Department, The United Steel Companies, Ltd., Stocksbridge) : Mr. Halliday has said almost all that I wanted to say, but I should like to reply to the last point raised by Mr. Carruthers. If it is a fact that breakouts of blast-furnaces are due to oxidation of iron infiltrating into the bricks, then the obvious inference is that a carbon hearth is liable to burn. There is a two-fold answer to this :

First, we have had patches of carbon bricks in use in our Appleby furnaces for two years now, and when they were inspected recently it was found that no more than ½ in. of their thickness had disappeared.   If this is all the wear which occurs during the first two years on the two carbon hearths just installed in Nos. 9 and 10 furnaces at Appleby-Frodingham, then we shall be very satisfied.   Secondly, and this is more academic, the amount of oxygen required to cause a breakout, by the formation of FeO in the bricks, is probably very small compared with that required to produce any appreciable burning of a massive carbon hearth.   Such burning as did occur would in any case be distributed over a wide and relatively low temperature range and would result in the main in a slight increase in porosity.   Even if this rose from 20% to 30% the bricks would still be as good as those specified on the Continent.

Another point which should be borne in mind is that, whereas in the oxidation of iron the oxygen is absorbed, in the burning of carbon, carbon monoxide is liberated which will fill the pores and reduce the risk of further air infiltration.   Even so, we feel that all reasonable precautions should be taken to ensure that the furnace case is air-tight, and in the No. 9 furnace we have installed steel plates in a horizontal layer below the carbon hearth.

Dr. G. R. RIGBY (British Refractories Research Association, Stoke-on-Trent) : The British Refractories Research Association has been giving much thought to the problem of hearth breakouts and we are there-fore very interested in the theory advanced by the authors.   In a paper by Mr. A. T. Green and myself to the West of Scotland Iron and Steel Institute in 1942 we suggested two possible causes of breakouts.   The first one de-pended on the shrinkage of the fireclay bricks under the com-bined influences of temperature, pressure and reducing conditions, while the second theory con-sidered the possible oxidation of the iron, the ferrous oxide thus produced slagging with the brick-work. Frankly, however, we have

FIG. C.—Thermal Conditions in the Brick-work of a Blast-Furnace Hearth.

tended to incline towards the first theory, since, when examining hearths, we have often found evidence of shrinkage taking place with the consequent opening up of the joints, but no evidence of serious slag attack by iron oxide.   It is therefore of great interest to us to read the findings at Appleby-Frodingham of this zone of ferrous-oxide slag.

The authors do well to stress the pronounced fluidity of certain types of iron.   Firms making two classes of iron of varying fluidities often experience breakouts only with the more fluid type.   On the other hand, there are firms making a viscous iron who have never been troubled with breakouts.   An appreciation of the great penetrating power of certain types of iron is therefore the first step in an understanding of breakouts.   It cannot be very long before the iron in the hearth has penetrated between the joints in the brickwork, no matter how tightly the bricks were laid.   To fix our ideas we might consider a hearth containing liquid iron at a temperature of 1500° C., the freezing point of the iron being 1100° C. and the outer face temperature of the brickwork being 300° C.   The location of the

1100° C. isotherm in the brickwork will represent the limit to which the iron can initially penetrate by way of the joints, and it probably takes the form of the line AA' in Fig. C. As the bricks surrounded by the molten iron begin to shrink under the combined influences of pressure, temperature and reducing conditions, so the joints in the brickwork will widen and even the pores of the bricks will eventually be found to contain iron. This will mean that the conductivity of that portion of the hearth where iron has penetrated will steadily increase, and in consequence the 1100° C. isotherm will recede further and further away from the hearth into the brickwork, taking up a position, say, BB'.

If conditions now became stabilised it is difficult to visualise how a breakout can occur. Even if oxygen penetrated that part of the hearth below 1100° C. which was sealed off from the furnace, and oxidation of the iron occurred with slag formation, the melting point of the slag could not be much lower than 950° C., and, accordingly, freezing of this slag would occur at positions corresponding to the 950° C. isotherm at, say, CC'. It is difficult to understand how oxidation of the iron can be a major factor in hearth breakouts, although it may well be a contributory factor.

Unfortunately, the above conditions are usually not stable, since the brickwork immediately in contact with the iron has shrunk to such an extent that it loses its key and becomes dislodged by the iron. The currents and turbulence induced in the molten iron during tapping must materially assist in this wearing back of the original hearth level, and it seems reasonable to assume, other factors being equal, that the greatest wear will occur in the vicinity of the tap-hole, where the eddy currents will be at a maximum. This wearing back of the hearth contour will again alter the position of the 1100° C. isotherm until it is finally situated so near the cooling staves that the iron finds a crack or weakness in the bricks which brings it into contact with the stave sectors.

It is now a matter of time before this continuous iron channel established between the hearth and stave sectors is enlarged by further shrinkage of the brickwork until sufficient molten iron passes along it to cut the staves and produce a breakout.

According to this theory, if the original contour of the hearth could be preserved so that a bear was not produced, breakouts could not occur; a relation between the amount of bear formed and the susceptibility to breakouts would therefore be expected. There are many furnace hearths recorded, particularly those with a coke-tar ramming, which have preserved their original contour and which have been free from breakouts.

The above theory satisfactorily explains the prevalence of breakouts in the region of the tapping hole. Breakouts are favoured by a fluid iron which has a freezing point considerably below the temperature of the hearth. Large-diameter hearths would also be expected to be more susceptible to breakouts, since larger hearths mean longer casting times, and the bricks in the vicinity of the tap-hole are therefore subjected to erosion for longer periods every day.

If we do not entirely agree with the authors of the Report regarding the origin of breakouts, we are in complete accord as to the remedy to apply, *i.e.*, carbon hearths and preferably prefired carbon bricks. We like carbon bricks, not so much because they will avoid the formation of ferrous-oxide slags, but because they remain volume-stable under applied stresses at high temperatures in a reducing atmosphere. We have tested carbon blocks from a number of sources, including some made by ourselves, and they do not show any shrinkage at 1650° C. under an applied load of 50 lb. per sq. in. Thus, if the iron penetrates the joints between carbon bricks in the hearth, these joints will not enlarge owing to shrinkage, and there will

be every chance of the hearth preserving its original contour, and the possibility of breakouts will be reduced.

Mr. W. A. AKHURST (Round Oak Steel Works, Ltd., Brierley Hill) : In the Iron and Steel Institute Special Report No. 18, dealing with the blast-furnace field tests carried out at the Appleby-Frodingham Company's works at Scunthorpe in 1937, I noticed that the irregular cross-sectional composition of the various-sized materials and fines, caused by the bell method of charging, gave rise to irregular CO_2 and temperature distribution, the easy way for the blast being up the centre of the stack and at the outer walls, CO_2 being low and the temperature high in these locations. It therefore seemed obvious that if the material could be of even composition
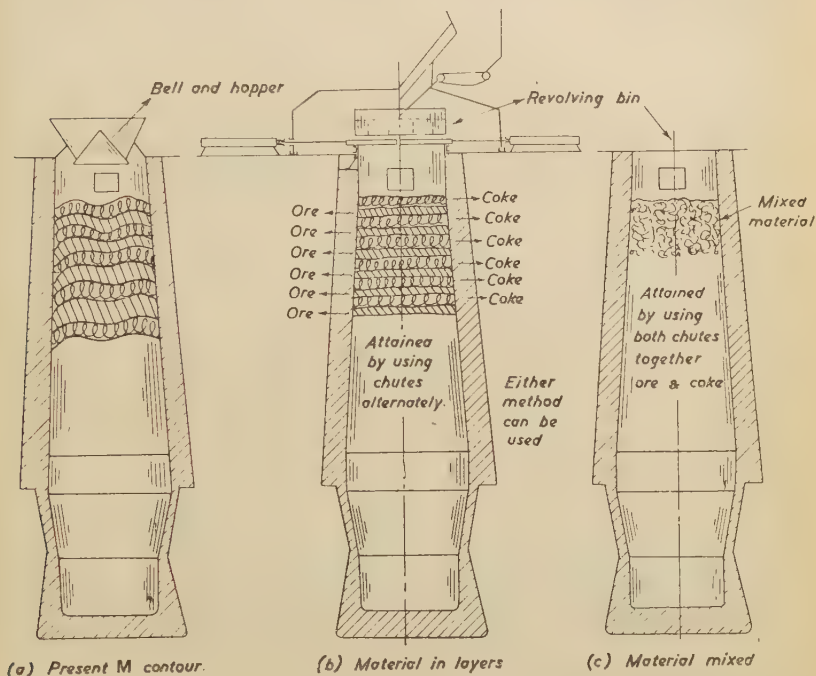
FIG. D.—Types of Stockline Contour.

across the furnace area the blast would be able to exert its upward pressure evenly, the temperature and CO_2 content would be more uniform and would therefore tend to promote more efficient reduction and quicker melting, and if the cross-sectional temperatures were about the same across the whole diameter there would be less liability to hanging and slipping.

In 1937, Mr. Hacking considered that until some method of charging other than the bell and hopper was used, present methods could not be perfect. Mr. Harrison, of Middlesbrough, said that some method other than the bell and hopper would have to be devised. Mr. Julius Behrendt, of Scunthorpe, said that so long as the centre circular crater existed with the circular bell and hopper, serious conditions would follow owing to bad physical conditions. All these gentlemen have asked for something better than the bell and hopper.

I have spent some considerable time in experimenting, and with the help of models have devised a method whereby the bell can be dispensed with. To illustrate this Fig. D illustrates three types of stockline contour; (a) shows the present M-contour across the throat of a blast-furnace caused by the misdirection of material by the conical bell at present used, (b) illustrates how material can be put into the furnace in layers of any predetermined depth and horizontally flat across the throat of the furnace and (c) indicates how ore and coke can be mixed if this is thought desirable.
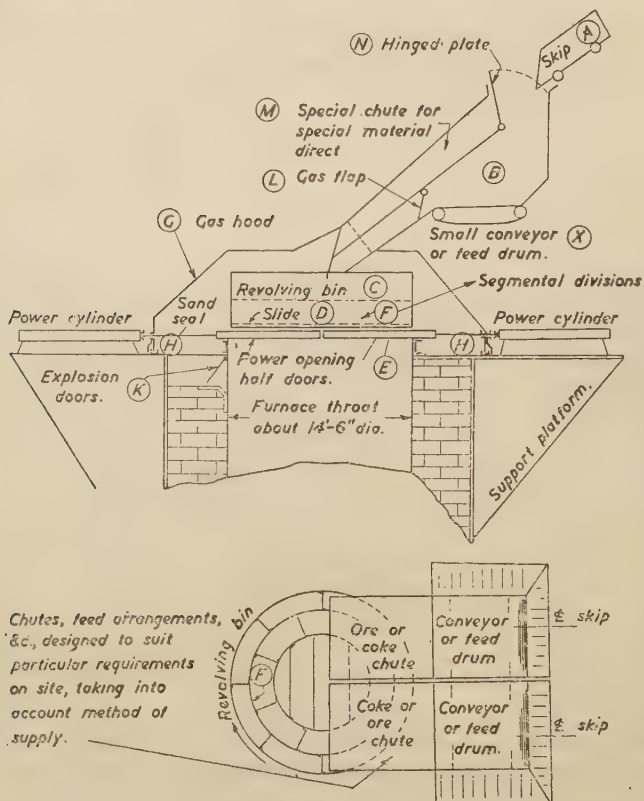
FIG. E.—Blast-Furnace Charging by Revolving Bin.

Fig. E is a sketch of the method which I would use to attain efficient charging. It comprises a revolving bin, C, which is subdivided circumferentially and radially. This bin revolves below the chutes supplying ore or coke, which are fed into the bin by a feed drum or alternative means. When the required depth of material is attained, the feed drum is stopped and the bin stopped. The loose bottom of the revolving bin is in two halves, D, and the bottom plates are withdrawn, allowing the material to rest on the two main half-doors. The final operation is to open the two main doors, E. It will be appreciated that, as the main half-doors open, the material in each segment uncovered falls vertically into the furnace,

and there cannot be any piling in the centre of the furnace.   The main doors can be of steel joists and plates, water-cooled if thought desirable, and operated by the best mechanical means available.   The revolving bin would have to be designed to have renewable wearing plates.   This bin would be power-driven and run on a large circular roller race.   The whole would have to be covered with a gas hood of plates, sand-sealed, with examination and access openings where necessary.

Another advantage of my system of charging is that, by fixing diverting vanes in the chute, the material can be directed so as to give any desired contour, whether M, V or the flat type.   If desired, finer material can be directed to the outer walls; in fact, the system is so flexible that any desired contour of the stockline can be arranged and obtained.

Dr. Saunders very kindly examined the model that I had made, and I am sure that he will vouch for the correctness of my statements.   I claim that by my method material can be placed in horizontal layers of even thickness, the amount, weight or depth being predetermined.   Fines are not isolated anywhere, but the whole remains intermixed.   It should be impossible for the blast and gases to find an easy route to the furnace top. The pressure, evenly distributed and passing through a uniform resistance, should deliver gases of a uniform temperature and CO_2 content, with resultant benefit to the final iron production and reduction in coke consumption per ton of iron produced.

Mr. R. FROST (Messrs. Guest Keen Baldwins Iron and Steel Co. Ltd., Port Talbot) : Mr. Elliot, in discussing remedies for breakouts, mentioned that America and Germany in earlier days both had a good deal of trouble from this cause.   In America they got over the difficulty by paying special attention to their manufacture and their brickwork.   Germany turned to carbon hearths.   They do not say whether that solved their difficulty so far as breakouts are concerned, but I do think that we could learn also from America.   The Americans have solved their difficulties; we know that they are running big furnaces with big outputs, and breakouts have been eliminated by the use of refractories.   It should be possible in Great Britain, I think, to produce refractories which come up to the American standard, and I suggest that investigations should be carried out on those lines.

Mr. Elliot mentioned that in his furnace operation he found it necessary consistently to run small tuyeres over or on either side of the tapping hole. We have had to do this at times, but prefer to run the same size of tuyeres all round the furnace.   We think it an advantage to do this if it is possible.

Mr. I. S. SCOTT-MAXWELL (Messrs. Colvilles, Ltd., Glasgow) : Mr. Elliot has asked for criticism, but I hesitate to criticise because I have a good deal less experience, and have not gone through all his troubles.   I cannot help thinking, however, when looking through his Report, that there must be something fundamentally wrong in the design of his furnaces which is accounting for the irregular stock movement, scaffolds and hearth breakouts.

He passes fairly lightly over the question of tuyeres and tuyere velocity, to which we at Colvilles attach a fair amount of importance.   We have been operating since the beginning of this year on a great variety of foreign ores which have had to be blended with home ore, and at varying production rates.   Consequently, we have had tuyere sizes of 5 in., 6 in. and 7 in. all round the furnace at different times, and also intermediate combinations of alternating 5-in. and 6-in., and 6-in. and 7-in.   We have blown wind volumes of from 26,000 up to 36,000 cu. ft. per min.   The furnaces, generally speaking, have gone well under all conditions, but they would not have

done so if the design had been incorrect or had insufficient attention been paid to tuyering. I have already asked Mr. Elliot for figures in connection with this, and will say no more meantime.

Mr. Elliot is somewhat dogmatic about figures for stack batter, bosh diameters, &c., in relation to the particular problems associated with Frodingham ore. The slag bulk at Appleby is very little higher than that experienced at Colvilles on Northampton ore, but I venture to suggest that we operated successfully on narrow-bosh furnaces, whereas Appleby are not so successful on a wide-bosh design. Will Mr. Elliot please tell us why he crushes the ore to the present small size ? He says that to crush larger would be undesirable, but he gives no reason why ; has he correlated this ore size with the time of travel through the furnace ? I have the feeling that he has not been able to obtain large enough wind volumes to get the furnaces moving because his bosh diameter is so large and because of the fineness of his burden. The result is that the furnace does not work in a regular fashion, and he will have a low tuyere velocity. With low tuyere velocities there is much action below as well as above the tuyeres. In effect, it would tend to scour the bosh brickwork and build up a scab at some point on the stack just above the mantel. With high tuyere velocity the reverse takes place and the tendency is to build a scab on the bosh and to scour the stack brickwork.

With regard to the general furnace dimensions, there is little uniformity of design, in spite of operation for so long on the same ores. I would draw attention to the distance from the tuyeres to the hearth bottom, which seems, on all except the two hand-charged furnaces, to be about 6 ft. 9 in. Can Mr. Elliot tell us why this figure is the same in so many furnaces of different size ? In the Colvilles 12 ft. 6-in. furnace the figure is 6 ft. 6 in., in the 18 ft. 3 in. it is 8 ft. 6 in., and in many American furnaces with 25-ft. hearths the figure is about 12 ft. Is Mr. Elliot of the opinion that such factors as low tuyere velocities, tuyeres near the furnace bottom and close proximity of tap-hole and slag notch have no bearing on hearth breakouts ? Further, all the Appleby furnaces except Nos. 9 and 10 are fitted with a lip ring on the large-bell hopper. Does this not give restricted flow and bad distribution ?

The furnaces at Colvilles are built completely solid in concrete, and that is a good way of keeping the air out if it is air that causes the trouble. Why does not Mr. Elliot do that ? In laying the hearth bricks we break the horizontal joints and the vertical joints are continuous, which is the other way round from which most people do. In other words, the iron cannot percolate in a horizontal plane towards the outside of the furnace, but only in radial vertical planes. It may be said that this will give a big salamander, and that, because the furnace is entirely enclosed in concrete, it is going to be difficult to get the salamander out. So it is, but the iron does not percolate far in the vertical plane, because it freezes. It will be necessary to blast the salamander, but the experience which we think we are going to get, and which has been obtained at Dagenham on a similar design, is that the salamander is very small. A few hours spent on blasting, therefore, are preferable to, and less costly than, breakouts during the furnace campaign.

Mr. T. R. Hodson (The Kettering Iron and Coal Co., Ltd., Kettering) : A striking feature of Section VII. of this Report is that, in spite of the assistance of the finest burden preparation plant in Great Britain, Mr. Elliot and his colleagues have still to solve the hardy interrelated problems of distribution, smooth stock descent and the use of high blast temperature, even though the burdens are not affected by the further complications of added limestone or calcined ore. Fig. 78 shows the disturbing effect on distribution of the varying angles of repose of two materials only, ore and

coke, while the details of stockline sampling on p. 207 show the horizontal and vertical segregation which occurs.

Mr. Elliot does not mention a further important physical property which, if I may coin a word, I will call " reboundability." It is this which determines the extent to which a piece of material will rebound after striking the throat protection or the burden materials. It varies widely, as it shown by comparing soft wet raw ironstone with coke. It is a potent factor, and particularly so when burdens contain a number of components and the V-stockline is used.

The Table of bell proportions given on p. 83 shows that in Appleby-Frodingham practice the area of the furnace under the bell varies from 43% to 59%. It shows also that with furnaces Nos. 9 and 10 some of the material, apart from falling from the bell, has to bounce or roll distances up to 9 ft. 9 in. radially to reach its final position. Segregation is inevitable, particularly in view of the variations in the property of reboundability.

Mr. Elliot's inclination towards the M-stockline, expressed on pp. 194, 196 and 205, is a logical development. As a result of accumulated experience, M-stocklines have been adopted at Kettering, and by trial and error the ratio between stockline and bell diameters is now 2 : 1, with only 25% of the area of the furnace under the bell. This seems to be about right for our burden materials and furnace dimensions. The resulting stockline is similar to that shown in Fig. 82, where No. 3 furnace at Appleby-Frodingham was filled to a depth of 17 ft. 3 in., except that the crests and valleys are well rounded. The materials fall directly from the bell to the stockline, so reducing in a large measure the effect of varying reboundability. The smaller and lighter bells permit a higher bell opening speed, and, as the charges contain calcined ore with fines, the segregation which would be caused by the filtering action of a slow-operating bell is reduced.

In our experience, the M-stockline has given various desirable characteristics, among which the more important are (1) free driving and regular stock descent, whether making basic iron or foundry irons with a wide range of composition; (2) sufficient peripheral gas flow and activity to prevent fines from dwelling at the walls and sticking, so that the bosh and shaft walls are kept clean, particularly the vital upper bosh and lower shaft; in consequence, our blast temperature varies from 1500° to 1600° F. according to furnace requirements, whether making basic or foundry iron; (3) flexibility; the burden can be varied from 50% raw and 50% calcined to 100% calcined without disturbance, although the latter material has considerable diversity of size and contains a notable percentage of fines; (4) throat protection and its attendant problems are eliminated; (5) contrary to fears, the usual bogey of M-stocklines, namely, the cutting-away of the shaft lining, has not appeared; (6) exploration from wall to centre immediately above the stockline has shown remarkable evenness in CO/CO_2 ratios.

Mr. Elliot discusses in Section IX. the difficulties of using higher blast temperatures at Appleby-Frodingham. Our experience at Kettering with smaller furnaces suggests that if he adopts the M-stockline he will make progress towards higher blast temperatures to meet his higher slag heat requirements.

Mr. JAMES DALE (Larkhall) : To the Appleby-Frodingham officials we owe a debt of gratitude for the publication of their experiences in hearth breakouts, a matter that they have investigated thoroughly. Those operators who have never experienced a real breakout are fortunate, and it is only to be hoped that they will benefit by reading the experiences of others as much as those who have actually experienced them.

It will be noted that many of the breakouts experienced at Appleby-

Frodingham have been in the vicinity of the tap-hole; this is probably the experience of others.

Many have originated through poor tap-hole stoppages, and it is disturbing to note that on many plants the tap-hole does not receive the care that it should. At some blast-furnace plants the opening of the tap-hole by oxygen is a regular procedure, whereas at others the method is used only when the crew fail to open the tap-hole by driving in a bar.

With the slender pipe usually employed in opening a tap-hole by means of oxygen there is usually little control of the direction, and in case the hole has been stopped against an iron run it is probable that the iron is forced into the weaker sections of the clay stop, causing veins of iron to be formed laterally to the hole. It is possible that the oxygen follows these veins of iron, resulting in a weak, short hole, allowing wild casts.

The clay stop of the tap-hole should be at least as long as the brickwork in that section, otherwise erosion will occur, and if this erosion takes place to any extent over a period, the danger of breakouts at the tap-hole section becomes a matter of concern.

At one plant with which I am acquainted, where there has been no trouble with tap-holes, a stop 6 ft. long or more can be attained at any time; at this same furnace, the oxygen lance is used only as an extreme measure.

We have all experienced light-weight casts due to short tap-holes, and as soon as the tap-hole length becomes normal and longer, heavier casts are obtained. A few months ago, on one furnace, after three days of one week's operation had passed, there was a shortage of about 135 tons between the iron input and output; this was due to a series of short holes. When normal tap-hole lengths had been restored this iron was cast from the furnace in just over 24 hr., in addition to the full day's production, making an additional cast necessary.

I am not by any means attributing all breakouts to faulty tap-holes, but I do emphasise that long tap-holes, which enable the furnace to be practically dried of iron and slag at each cast, are a much safer proposition, lessen the chances of a breakout, and also lessen the seriousness of breakouts if they do occur.

While the lost tonnage due to lost operating time is assessed by Mr. Elliot in Table LXXVI., the necessity for having to adopt unequal blast distribution, by plugging tuyeres in the vicinity of the breakout, cannot but give inefficient operation.

The distance from the centre of the tuyeres to the hearth should be a matter of consideration, as it appears that this distance has been increased over the last few years on the large American furnaces.

In the illustration of a typical 1000-ton furnace shown in Fig. 10 of Haven's paper,[1] it will be seen that the total height of the hearth is given as 11 ft. 9 in., or 10 ft. from the tuyere centre, the corbelled brick section being 2 ft. 0½ in. high. It would appear that an additional height in the hearth section should be a little insurance against breakouts. In the case of Nos. 9 and 10 furnaces at Appleby-Frodingham this distance (from tuyere centre to hearth) is slightly less than 8 ft.

I agree that consideration should be given to the location of the cinder notch relative to the tap-hole, and that it should be kept a reasonable distance from the latter. In many British blast-furnaces the slag notch just enters the inner wall of the furnace; this is usually a distance of 12–14 in. in American installations, and tends to lessen wall corrosion in that section.

Tuyere areas and wind velocities should also be considered, as it is only logical to assume that lower velocities will cause erosion of the hearth walls.

From Figs. 87, 88 and 90 it appears that there were two cast-iron stave coolers placed inside the steel-plate hearth jacket. Do these embrace the sections of the two cinder notches and tap-hole only, and is there any lagging between them ?

It would be interesting to know the reason why the iron and slag temperatures were so much higher than those usually obtained.

Mr. G. A. YOUNG (Messrs. Richard Thomas & Co., Ltd., Ebbw Vale) : That the quality of the iron may be a factor in furnace breakouts appears to be supported by the experience at Ebbw Vale with a Treadwell car ladle which was being used as a mixer, and which was lined with 42% alumina firebrick. The lining lasted only three to four weeks. I believe it is American practice to line hot-metal receivers with firebrick and that good lives are obtained, whereas in Great Britain hot-metal receivers of the inactive type for high-phosphorus iron are lined with magnesite bricks, and only indifferent lives are obtained. Since it is not possible to see what is happening in a blast-furnace, it may be of interest to mention what is observable in a receiver. At Ebbw Vale the hot metal is poured into the receiver through the inpouring spout on one side and out through the outpouring spout on the opposite side, and it is significant that rapid wear of the barrel lining takes place on the side of the receiver along which the iron runs to the outpouring spout. The fact that the lining is worn away by the turbulent action of the iron appears to support Mr. Elliot's theory that high-phosphorus iron may be a factor in furnace breakouts.

Hanging and slipping in a blast-furnace may be attributable to the coke as much as to the ore making up the burden. The Appleby-Frodingham management have done an excellent job in blending so many coals and in obtaining such consistent results, but things are happening outside the coking plant which affect coke quality and which cannot be placed at the door of the coke-oven manager ; I refer to the inclusion of shale and inferior coal in increasing quantities in coal supplies to-day, so much so that the physical properties of the coke are lowered. If something is not done to arrest this deterioration by supplying cleaner coals, I can see that we are going to have a great deal more trouble in maintaining our blast-furnace practice in the future than we have had in the past.

Mr. R. SHARP (The Stanton Ironworks Co., Ltd., near Nottingham) : There is one point in Mr. Elliot's paper which I should like to see corrected, and that is on p. 82, where he mentions Sir Lowthian Bell's Ormesby furnace. It may not sound very important, but Sir Lowthian Bell owned the Clarence Ironworks, and all his experiments were done there. Mr. Charles Cochrane was the owner at that time of the Ormesby works. The whole reference in this paper is incorrect, because there was a great dispute in those days between the two of them on this very question of furnace capacity. It is stated in the paper that Sir Lowthian was in favour of the large furnace, but he certainly was not, whereas Mr. Cochrane was. Sir Lowthian used to give all his papers to this Institute, but, for some reason which I cannot explain, Mr. Cochrane used to present his papers to the Institution of Mechanical Engineers. It would have been better if Mr. Cochrane's papers had been given to The Iron and Steel Institute, as no doubt more practical men would have been present to discuss them.

There were two or three other points of dispute between them in those days which are still important. For example, Mr. Cochrane was in favour of calcining the limestone, and Sir Lowthian definitely was not. Sir Lowthian thought that the lime reabsorbed the CO_2 in its descent down the furnace and that it had to be again driven out ; Mr. Cochrane proved

to his own satisfaction that that was not so. Sir Lowthian did most of his experimental work on a furnace, which has already been mentioned, of 12,000 cu. ft. capacity, while the furnace to which Mr. Elliot refers here had a capacity of 33,000 cu. ft. It had an 8-ft. well, a 28-ft. bosh, a 23-ft. throat and a 15-ft. bell, and I think was 93 ft. high. The material took something like two days to come through. It eventually stopped in blast for thirty years or more and made over 1,000,000 tons of iron, and I believe that when it was blown out the bosh diameter was something over 40 ft. It was a remarkable furnace; it started by making 400–500 tons a week, but they gradually pulled the tuyeres back until the hearth was extended from 8 ft. to 11 ft., and the furnace then made 850–900 tons a week. The coke consumption used to be about 21 cwt.

Sir Lowthian's furnace, in the very old days of beehive coke and Cleveland calcined stone with 42% of iron, had a coke consumption of about 20½ cwt., but later I had charge of that furnace for many years and it was in blast for over ten years, its coke consumption being 22·8 cwt. and its make about 840 tons a week with by-product coke and Cleveland calcined stone containing 37% of iron. This question of capacity, therefore, was an important one in those days, and to some extent it is not yet settled.

The third point of difference between them was the important one of blast temperatures. Sir Lowthian said that the effective limiting temperature was about 1000° F., but Mr. Cochrane thought it could be raised with advantage to 1450° F. However, when I took charge of the Clarence furnaces in 1915 we were calcining the limestone and using a blast temperature of 1450° F. for the making of Cleveland foundry iron.

Coming to the question of the operation of furnaces at the present time, Mr. Johnson this morning reported some very good figures from the Kettering ironworks, and quoted the coke consumption to the second place of decimals—21·23 cwt.—but he did not tell us the percentage of scrap which he was using. This is very important, as we have to reckon these things up, especially when we are working with materials of a similar nature. I rather think that Mr. Johnson is using some 5 cwt. of scrap to a ton of pig. It is important to know how much scrap is being used.

Mr. Scott-Maxwell told us that at Colvilles they could not make low-silicon iron. He told us what the silicon was, but not what the sulphur was. It would be interesting to know that.

Mr. Scott-Maxwell : The sulphur was 0·08%.

Mr. Sharp (continuing) : That is a very good figure. We find in smelting 100% Northampton ores that unless we use a modification of what is now called the acid process we cannot get any regularity at all. It would have been an advantage if Dr. Colclough had given in his paper some particulars of the kind of iron that was produced on this 1 : 1 lime/silica ratio, because my experience is that in Northamptonshire you will probably get an average sulphur content in the iron of something like 0·25%, and I have found by experience that this 1 : 1 ratio is not absolutely essential in the process; we did better work by increasing the ratio to about 1·1 : 1—35 of lime to 32 of silica—and also by adding enough dolomite to put the magnesia up from 4% to 7%. This gave a hotter and smoother-working furnace and brought the sulphur down to about 0·1%, and by desulphurising this we could make an iron which fitted the specification which we were asked to meet by the Iron and Steel Control; in fact, our average sulphur is about 0·04–0·05%.

PREPARATION OF THE BURDEN.

(Second day, morning session.)

Dr. T. P. COLCLOUGH introduced this subject for discussion.

Dr. H. L. SAUNDERS (Imperial College of Science and Technology, London) : I think we can say that there are two ways in which the burden may be prepared; the first is external—drying, calcining, blending and sintering—and the second is internal, by means of controlled distribution. I will confine my first remarks to sintering. Quite a cursory examination of commercial sinters leads one to the conclusion that they are generally made at too high a temperature, and this is fully borne out by the results of reducibility tests in the laboratory. The aim should be to make the reactivity of the sinters as near to that of the parent ore as possible, and this would demand a considerable amount of experiment. There is a big difference between the physical textures of sinter and ore as well as in their chemical properties. The pores of an ore are much smaller than those of a sinter, and that is the reason why the South Kensington porosity test in its original form was not suitable for assessing sinters, there being no real distinction between voids and the larger pores. This test has since been modified by the introduction of another measurement based on the total volume change when the sample is submerged in mercury and submitted to a pressure increment of 1 atm. This pressure porosity, taken in conjunction with the previous data, can be used for the comparison of sinters with one proviso; the sinters must not be of a totally different character. As long as no disproportionately large changes are made in the composition of the sinter mix, the porosity test can be usefully employed. Whilst the laboratory reduction estimation is, of course, the best, the porosity test has the possibility, with a slight modification, of being made portable, and so could be used actually at the plant.

Even an indifferent sinter may be preferable to large quantities of fines in the average blast-furnace, but good sinter should not be a rarity if greater control were exercised during production. Sinter confers upon the burden a measure of openness of texture which can hardly be secured by any other means. It differs, however, very radically from ore in its behaviour towards CO at low temperatures. Carbon deposition does not run to excess with a sinter. The finely divided carbon does not clog the interstices, the blast and general movement of the burden being sufficient to dislodge it, and the reducing gases can still perform their useful function of oxygen removal. Sinter, like good coke, should withstand the crushing forces within the furnace. When ore reaches the hotter zones the impregnated carbon reacts, but with the usual sinter any direct reduction occurs at the expense of the coke. If, therefore, an excess of coke were used in the sinter mix, and the suction were reduced so that the temperature in the sinter bed was not excessive, some of this carbon would be trapped in the sinter matrix and, because of its more intimate contact, would be usefully employed in oxygen removal later on in the furnace. The excess carbon is not lost, and a corresponding reduction in the coke requirements of the furnace should follow.

Bonding in a sinter is a highly complex process, and it often happens with these self-fluxing Lincoln ores that a slag is formed preferentially, especially when the amount of reduction is small. The melting points of the Appleby-Frodingham sinters seem very low, and suggest that too much ceramic bond is present. This is a pity, and more so if it happens to be of a fayalitic character as well, because of its low melting point, so

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that porosity can be destroyed before the material even reaches the furnace. The solution lies in the selection of the raw materials whenever possible. Too often there are dumps on the works that have to be cleared, irrespective of suitability. An alternative is the use of additional coke, and this seems to be borne out by the reducibility figures for sinter No. 7 in Fig. 35 of Mr. Elliot's Report, where the coke was at a maximum.

Considering that perhaps 8% or 9% of coke, including the coke of the flue dust, is about normal for Appleby-Frodingham practice, it is rather surprising that in most of these sinters the initial deoxidation is so low; 6000 cu. ft. of air per cwt. represents a substantial excess over theoretical requirements and suggests that oxidation is occurring in the later stages of the sintering process. This represents an indirect carbon loss. Hence the necessity for suction control from ignition onwards throughout the entire process until the sinter is ready for handling. The relative quantities of all ingoing materials to the sinter plant need as careful regulation for maximum economy as those going into the blast-furnace.

When using quantities of up to 70% of flue dust (Table XX., Report No. 30), the fact that the reducibilities are decreasing progressively suggests either that temperatures generally increased or that the suction was abnormally high, and the absence of any progressive variation in the Fe_2O_3/FeO ratio suggests non-uniformity of the product. I can only agree with Mr. Elliot's statement that good sinter cannot be made without the use of return fines in so far as it relates to present commercial methods. There is no special difficulty attending sinter-making on a laboratory scale, where all conditions are under the necessary control, and quite high reactivities can easily be obtained at will. However, since in practice we always get these return fines the best use should be made of them. Magnetic separation in addition to normal screening might be employed, the coarser magnetic fractions being used for bedding and the remainder returned to the mixers. I heartily support Mr. Elliot's view of the need for a systematic investigation of all the factors involved in the making of the best sinter possible.

Turning, now, to the question of distribution, even when the ideal burden for a particular furnace has been worked out, as Dr. Colclough very rightly points out, the blast-furnace can no longer be regarded merely as a machine that is capable of utilising anything. The whole of his arguments on efficiency depend upon the attainment of the maximum quantity of CO_2 for the coke burned at the tuyeres, and this surely means the maximum possible contact between every piece of iron-bearing material and the reducing gases, so that oxygen exchange may be facilitated at all points. This can generally be achieved only by uniform distribution. Given this, the passage of the gas will be uniform and the burden will change uniformly in composition as it descends uniformly from the stockline to the hearth. Many blast-furnace problems to-day are bound up with the steep radial temperature gradients consequent upon irregularities of gas flow. Reactions of diverse character are taking place in close proximity, and anything in the nature of a slight slip upsets everything. Distribution must be improved. The one obvious answer is closer size grading. What, then, is to be done with all the material left over after the selection is made? Dr. Colclough suggests uniform charging with three gradings, and, apart from the fines due to handling and charging, segregation under such conditions would be reduced to a minimum.

In the ideal burden the pressure drop across a horizontal layer of uniform thickness will be the same between corresponding points. Is there any other method of approach towards this end? Suppose the section in question to be built up in two layers of equal thickness, in which the distribution patterns are reversed—*i.e.*, in the lower half the

coarse material is at the centre and the fines are near the wall, and in the upper half the fine material is at the centre and the coarse near the wall—then there would be no preferential channelling of the gas. The thinner the layers of complementary charges the nearer would be the approach to the ideal. Alternatively, combinations of radial and vertical distribution patterns might be utilised, the particular cycle of operation depending on the furnace lines and the nature of the burden. Such a scheme would, of course, necessitate a modification of the normal bell-and-hopper charging, though in its simplest form this would involve no more than the elimination of bell overhang and an additional gas seal.

A system of cross and mixed charging, an example of which is given on p. 200 of Mr. Elliot's Report, goes one step in the right direction, but only density segregation is involved here, and this is not enough; size segregation must be utilised as well. The need for better distribution is universally admitted. It only remains to ascertain the best method for the nearest approach to the ideal.

I entirely disagree with Mr. Elliot that work on such lines is wasted effort. Uniform distribution provides the datum line from which to measure variation. If distribution can be such that by variation of the charging cycle any modification can be secured at will, that should be sufficient to satisfy the demands of everybody.

Mr. E. M. SUMMERS (Stanton Ironworks Co., Ltd., near Melton Mowbray) : As the operator of what I suppose by comparison must be termed an old-fashioned blast-furnace plant, I am particularly interested in this morning's discussion. We are operating at present on a burden of 60% brown Northampton ore and 30% carbonate ore, the latter being calcined in gas-fired kilns. The defects of this practice are, of course, obvious, arising as they do from the large size of the carbonate ore and the high proportion of fines in the brown Northampton ore. The remedy would seem equally obviously to be in crushing, screening and sintering the ores, but I am not at all sure that for carbonate ores the process of calcination can be dismissed so lightly. After all, calcination must take place somewhere, and if it takes place within the furnace itself CO_2 is given off which reacts with the descending coke, resulting in a loss in fuel efficiency. Both Dr. Colclough and Mr. Elliot mention this point, and I think they will agree that we cannot expect to achieve the optimum CO/CO_2 ratio or a minimum coke consumption if we charge raw carbonate ores into our furnaces.

I submit that it would be better practice to crush and calcine the carbonate ores at the quarry, so as to derive full benefit from the saving in transport charges, and then to screen and sinter them together with the Northampton ore at the blast-furnace plant. The ores that I have just described resemble in some respects those used by Mr. Elliot at Appleby-Frodingham, and I feel sure that he has given this point careful consideration; it would be interesting to know why he decided not to use calcination as part of his preparation scheme.

Dr. A. W. GROVES (Mineral Resources Department, Imperial Institute, London) : As one who for the last four and a half years has served as the geologist to the Iron and Steel Control, I should like to comment on the subject of the beneficiation of our low-grade bedded ores, and, since geology is at the root of the whole matter, perhaps I may be pardoned for doing so. Quite apart from sintering and calcining, from the point of view of their possibilities of beneficiation iron ores fall roughly into two sharply contrasted groups : Those where the bulk of the iron is

present as an iron oxide mineral, and those where the bulk of the iron is chemically combined with slag-forming constituents.

In the ores of the first group, the iron oxide mineral may be magnetite, hematite or limonite, using " limonite " to cover several hydrated iron oxide minerals. Of these, magnetite is so amenable to magnetic separation that even fine-textured ores can be separated magnetically after crushing. Hematite can be beneficiated only if it occurs in comparatively large particles, each particle containing little impurity. Clay can be removed from such an ore by simple washing, or a sufficiently coarse quartz-hematite aggregate can be beneficiated by the method of sink-and-float in a medium of suitable density. Limonitic ores will probably prove amenable to a reducing roast and magnetic separation in most cases, though they might also respond to washing.

Very few British iron ores fall into this first group. The possible exceptions are the minor occurrences of magnetite, of which more have come to light as the result of war-time prospecting by the Ministry of Supply, though none is being worked, some of the oxidised outcrop ores, and certain of the limonite-oolith rich ores of Frodingham and elsewhere. The oxidised outcrop ores have already been largely extracted. In effect, therefore, there remain only the ores that are rich in limonite ooliths in their unweathered underground extensions, but even in these much of the iron is often present in forms other than the oxide.

It is the second group into which the great bulk of the low-grade Jurassic iron ores of Great Britain fall, and their beneficiation undoubtedly presents very difficult problems. When the iron of these ores consists dominantly of the carbonate they are, of course, calcinable, and when they contain a considerable proportion of limonite in fairly discrete particles, as, for example, in ooliths, there are some possibilities of beneficiation by a reducing roast and magnetic separation, or perhaps even by washing in some cases; but the numerous iron ores in this country containing chamosite must be expected to give rise to the greatest difficulties in the way of beneficiation.

Other outstanding difficulties presented by our low-grade iron ores are the intimate intermixture of their constituents and their rapid variations in mineralogical composition, from chamosite to siderite or limonite, or mixtures of all three, both vertically from bed to bed and laterally. Often the nature of the slag-forming constituents is just as variable. These variations are well brought out in Section II. of Mr. Elliot's Report. With such rapid lateral and vertical variations in the ore minerals no less than in the other minerals the difficulty is to decide which mineral should be eliminated. A method of beneficiation suitable for one band in a quarry face can scarcely be expected to suit the half-dozen or so other bands in the same face.

The worst difficulty of all, perhaps, is the ore mineral chamosite, which, in addition to its iron, commonly contains about 25% of SiO_2, $15-25\%$ of Al_2O_3, several per cent. of MgO and a little lime; and chamosite is present in many of our low-grade ores.

Turning to those German iron ores that were being beneficiated before the war, it would appear from a review of the literature made by my colleague Mr. Deans in the Mineral Resources Department of the Imperial Institute that the following generalisations might be made. In cases where the Dogger ores were successfully beneficiated, the iron is present mainly as limonite ooliths, and silica is present in large amount as sand. A reducing roast followed by magnetic separation was therefore possible. In the case of certain Cretaceous ores of a soft nature, clay matter is removed by simple washing. Where, therefore, beneficiation has proved successful in Germany it would appear that the mineralogical and petro-

logical conditions were more favourable than in the case of the bulk of our ores. In other cases in Germany it is significant that repeated attempts at beneficiation up to 1939 had failed.

The problem, therefore, is first a mineralogical one and secondly that of ore dressing, but full knowledge of the mineralogy is the first essential, so that the first requisite in the survey suggested by Dr. Colclough is the mineralogy and petrology of the British iron ores. A very substantial contribution to the mineralogy and petrology was afforded some twenty years ago by the work of Dr. A. F. Hallimond, published in Vol. XXIX. of the Geological Survey's *Special Reports on the Mineral Resources of Great Britain*. But much detailed work remains to be done on this aspect of the problem before beneficiation tests commence. The outstanding question, therefore, is who is to carry out the work; and we have been told this morning that the Research Association has been asked to do so.

The task should, in my opinion, be a thoroughly co-ordinated piece of national research. In the United States of America such a problem would probably be undertaken by the Bureau of Mines, but in Britain we have no comparable body; neither the Mines Department nor the Geological Survey is staffed or equipped to carry out all aspects of such a major research. For national co-ordinated research on coal we have the Fuel Research Station, but for iron ore we have no corresponding Government department.

I venture to express the opinion that, with some possible local exceptions, the difficulties in the way of beneficiating most of our low-grade ores are such that the problem may for long remain unsolved, because ore dressing, if and when found possible, may well prove uneconomic. A tin ore worth, when concentrated, perhaps £150 to £200 a ton can carry a considerable expenditure on ore dressing, but how much can a phosphoric iron ore stand, even if it is enriched to 40–50% of iron? The answer is, I should imagine, not more than a few shillings a ton. We have also to bear in mind that any form of beneficiation of our low-grade iron ores will have for its final stage either drying or briquetting or some form of agglomeration. In that case it may well prove impracticable to proceed beyond the stage where a constant blend of ores is fed to the blast-furnace and the burden is enriched as far as possible by sinter prepared from a blend of ores known to afford the optimum sintering mixture.

Mr. R. P. TOWNDROW (Cargo Fleet Iron Co., Ltd., Middlesbrough): I have a very limited experience in this industry compared with that of most of my audience, but I wish to put before you the experiences on our plant after one year of very intermittent operation of an ore preparation plant, and also to bring out, in support of Mr. Elliot's plea for frankness, one or two of our difficulties.

The burden on which our furnaces worked before the war consisted of 50% of Swedish ores, and, in common with many other plants on Tees-side, when supplies of rich ores were no longer available some very drastic changes in blast-furnace practice had to take place, and consequently for most of the war years the operation of our furnaces could only be considered as highly unsatisfactory. We were working on Northampton ores, half of our supplies coming from a pit which in the calcined state gave us 0·5–0·6% of sulphur. In all cases the calcined stone had a very large proportion of fines and dust. The silica/alumina ratios were not favourable for producing low-alumina slags, and the furnaces in general were working in a very unsatisfactory manner. It was therefore decided to put in a crushing, screening and sintering plant to deal with these ores only. The sprinkling of foreign ores which we managed to obtain it was not proposed to treat at all.

I should like to compare three periods in the operation of the plant. The first, which we might take as typical of possibly the most unfortunate period of the working of the furnaces, was immediately prior to getting the ore preparation plant into operation. The figures are the average for a four-monthly period. The burden was a mixture of raw and calcined material which I have already described, and we had in addition 7 cwt. of foreign ore per ton of pig, and between 2 and 3 cwt. of scrap and bought pig iron. Our coke consumption was 25·2 cwt. Our consumption of ores and fluxes per ton of pig was 59·2 cwt. The average weekly output from two furnaces of 14-ft. hearth diameter was 2756 tons. It will readily be appreciated, therefore, that that is a performance of which we are by no means proud. The quality of the iron was very variable and very bad most of the time. One of the furnaces had a hearth so badly built up that it was not uncommon to flush iron over the notch after running about half a ladle of slag. Numerous expedients were tried, including all manner of slugs, pebbles, fluorspar, &c., to try to get the furnace hearth down, without any permanent success.

The next, an interim, period that I should like to describe followed a jump of five or six months, during which there was, if possible, still more disastrous operation, including a breakout at the tap-hole on this particular furnace. The repair of the breakout was followed by the discovery that water had been leaking into the furnace during the whole period that it was off blast, and when we withdrew a suspected cooler the water ran out of the furnace like a tide for an hour and a half, which did not encourage us to think that we had a very good chance of recovery in the case of that furnace. Be that as it may, within less than a week the furnace was running four ladles of slag over the notch and we were tapping the iron from the bottom tap-hole, and there has never been anything serious the matter with the furnace since.

Also during that interim period, owing to misguided efforts to reduce the coke consumption by overloading the furnace, we succeeded in getting the furnace so severely scaffolded that it would not drive at all. We managed to remove that scaffold by the relatively simple means of blowing the furnace down to about the top of the bosh and filling it up slowly. That furnace has had no trouble of that nature since, but we do feel that the cause of scaffolding and bad driving on our furnaces is very closely linked up with the ore/coke ratio, and more so in that sense than with any particular chemical phenomenon associated with the burden. The driving of our furnaces and the load that we can put on them do not appear to be governed by thermal considerations, because in all cases the loading of the furnaces is limited, not because the silicon is coming too low and the sulphur is too high and not because we cannot supply heat to the furnace, but because the furnace ceases to drive; and we have to look a long way further than thermal considerations to find how to get our ore/coke ratios to a reasonable figure.

I now come to the second period, by which time our ore preparation plant was in sufficiently full production to crush, screen and sinter the whole of the Northampton portion of our burden. In the meantime we had discarded the use of pig iron and were using a small amount of destructor scrap and turnings, which most of us on the North-East Coast are using, with the result that our consumption of ores and fluxes per ton of pig increased from 59·2 cwt. to 63·59 cwt. Our coke consumption showed a small increase, to 25·6 cwt., for the very much poorer burden, and our output increased from 2756 tons to 3013 tons a week. These figures are for a full month's operation.

These results were highly unsatisfactory in one sense to everybody concerned with the management of the plant, because it was being

confidently prophesied that the coke consumption would come down by about 4 cwt. as soon as the magic material sinter was put into the blast-furnace. However, I am of opinion that had we been able to continue that particular working long enough to get our furnaces thoroughly cured we might have got the results anticipated; but, owing to the demands of war transport at this stage, we received, in common with many other operators in the district, a severe cut on our Northampton stone. The Ore Control said, "You have been producing fines for about six months; you now have a sintering plant, so that you can use them up." We had, therefore, to suspend crushing operations entirely, apart from producing a small amount of material for bedding on the sinter plant, and our burden since then has consisted of run-of-mine Northampton stone and sinter produced from the fines that we had already made, and, as a gift from the gods, a somewhat increased allocation of foreign ore, which brought our foreign ore per ton of pig up to about 12 cwt.

There is one point that I want to make clear about our sinter. Owing to the fact that the larger proportion of our stone is calcined before we crush it, the resulting sinter has very little if any greater iron content than the material from which it is made. When we have crushed and sintered, therefore, we have usually in the crushed and graded stone a material of slightly lower iron content than the original material, with a slightly more favourable lime/silica ratio, and a sinter with very little more iron content than the original material, less porosity, and a very much higher silica/lime ratio. We can therefore say, as far as our ore preparation practice is concerned, that we get no enrichment of the burden as a whole, we get rid of very little volatile matter, and the only benefits to be expected are those to be gained in a purely mechanical sense from the elimination of fines and the grading of materials into reasonable sizes, while the only chemical benefit is the reduction of sulphur in the high-sulphur fines, which we get to the extent of from 50% to 60%.

The third period of that operation which I should like to quote to you I can compare only with the pre-war burden, because the burden which we are working now is so much richer in iron than anything we have worked since the beginning of the war. During the last two or three months our average output has been running around 3120 tons a week, with a coke consumption of 22·85 cwt. and a consumption of ores and fluxes of 55·31 cwt. per ton of pig. We can compare that with the pre-war practice, when the consumption of ores and fluxes was only 47·5 cwt., as compared with 55·31 cwt., and the coke consumption was 22·6 cwt., which, in view of the higher ash content of war-time coke, might be regarded as equivalent to 22·85 cwt. of war-time coke. So, merely by the use in our burden of sinter which is free from fines, and the porosity of which is probably less than that of the Northampton ore from which it is made, and using all the rest of our calcined Northampton ore in the run-of-mine state, we are now working with a burden/coke ratio of 2·42, as compared with the pre-war ratio of 2·10. We are looking forward with keen expectation to what we hope will be the very near future, when the removal of transport restrictions will once more allow us to get the benefit of screened and crushed ore instead of the run-of-mine ore, and we hope that we may be doing something worth talking about by the time of the next Meeting.

Mr. T. EASTWOOD (Geological Survey, London): As a geologist, I am naturally much more interested in the provision of the raw material than in what happens to it in the furnace, but in all stages where raw materials are being used the geologist does undoubtedly come in, and I think, too, that better use could be made of the geologist, and particularly of the

petrographer, in some of your blast-furnace problems. Dr. Groves has mentioned the valuable work carried out by Dr. Hallimond, of the Geological Survey. This followed a fairly comprehensive reconnaissance survey of the iron ores during the last war. During this war, from one-quarter to one-third of the staff of the English Survey have been engaged on the survey of the Jurassic ironfield of the eastern and southern Midlands. A great deal of their work will appear in the form of geological maps, but these will be supplemented by other maps which will deal with the constitution of the ore, the thickness, the nature of the cover and so on. A memoir will embody the principal results.

All this work has meant a good deal of very close co-operation with iron ore companies. Unfortunately, however, many of the data supplied to us have been of a confidential nature, and as such we treat them. I welcome this Report, therefore, as showing that there is some change of heart, perhaps, among the iron ore people with regard to the exchange of information. I may mention that the coal trade was in much the same position twenty or thirty years ago, when everyone refused to exchange information with his neighbours.

Dr. Groves also drew attention to the fact that the Jurassic iron ore is really a mixture of minerals, and yet very often people seem to regard it and treat it as if it were just a chemical substance of more or less the same composition. It is quite possible that some of your difficulties do arise from this mixture of minerals, and in this connection I would suggest that in the sampling of faces and of borings greater attention should be paid to the natural sub-sections in the bed, and that your chemical investigations should be followed up by petrographical examinations to know what minerals are in the sub-sections with which you are dealing, and also what you may expect from the proportions of certain minerals.

Dr. Groves mentioned that there is no institution doing for iron what the Fuel Research does for coal. We of the Geological Survey are short-handed. Recently, as I have said, we have had between a quarter and a third of our staff on iron ore. You may say that we have neglected you for a good many years, and that may be true, but we have many masters to serve, and until we can get more geologists we cannot devote any larger proportion of our staff at any time to any job, so that the remedy there is partly with yourselves. I would suggest, however, that wherever you have any problems even remotely connected with geology you should refer some of them to the Geological Survey. We may not be able to supply the answer, but we may be able to supply some means of tackling the problem at a later stage.

Mr. R. FOWLER (Messrs. Richard Thomas & Co., Ltd., Ebbw Vale) : For many years it has been realised that the proper sizing and preparation of ores, limestone and coke are essential for the best blast-furnace practice. It is also recognised that all fines should be extracted from our bulk ores and sintered. I appreciate the value of Dr. Colclough's paper, in which he tells us how we should treat our ores to get the best results as far as fuel consumption is concerned in our furnaces, but it must not be overlooked that we are not standing still, that nothing is being neglected and that we are trying to work in this direction.

Much practical work and many field tests have been carried out in the washing and dehydration of Northampton ores in order to eliminate a large proportion of the gangue-forming constituents, silica and alumina, in the fine state that still adhere to the ores, even after they have been crushed and screened, owing to their wet and sticky nature. This would eventually lead to a lower silica and alumina content of the ores and the sinter made from them, and in turn give a lower slag volume, less lime-

stone to be used as flux, and eventually a lower coke consumption. If, however, we are told that we must not spend our money in this way we cannot go any further at present, and we must wait for the time when we are free to spend our money and can make progress.

The proper preparation of all raw materials to be used in the furnace burden and the proper methods of charging are so well known that I shall not take up time by dealing with them. Differences in the reducibility of iron ores have long been recognised by most blast-furnace operators, and at this point I should like to put on record our appreciation of the work done by Dr. Saunders on the reducibility of iron ores. These reducibilities have been in many cases established by laboratory investigations and research work. It has been proved that limonite ores will reduce more readily than the more dense hematites and magnetites. What we do require, however, for blast-furnace operation is quantitative information which can be applied in the blending and mixing of our ores, so that each ore can be crushed to its proper size to give us the assurance that they can be reduced further up in the stack of the furnace.

Reducibility and porosity are very closely associated, and quantitative measurements of these two important characteristics will go a long way in helping to solve some of our major problems as far as fuel economy is concerned and to produce better gas/solid contact within the shaft of the furnace. In conjunction with the physical condition of the burden we must also take into consideration the question of its chemical condition and the type of slag which we have to produce to maintain the quality of the iron that we make.

To-day it appears that we have four groups of blast-furnace practice in the British Isles. In the first we have an ore burden where the sulphur content of the ores is so low that you can run with a slag ratio of 1 : 1 and the sulphur saturation of the slag is only about 1%. In this case the fact is beyond doubt that a furnace operating under these conditions with an acid bosh slag and lower slag volume will produce more iron with a lower coke consumption. These conditions can be brought about by a careful selection of Northampton ores, which are low in sulphur content. Unfortunately, all plants are not blessed with these favourable conditions.

Secondly, we have conditions where the sulphur content in the burden is such that you can work on an acid burden with a slag ratio of 1 : 1, where the sulphur saturation of the slag will probably run to about 1·8% and where the sulphur content of the iron may be as high as 0·4%. Here we have to remove that sulphur somewhere outside the blast-furnace, by desulphurising two or three times before the iron is in a suitable condition to be used in the open-hearth or Bessemer plant.

Thirdly, we have an isolated group. I refer here to the Lincolnshire practice as outlined in Mr. Elliot's Report, where siliceous Northampton ores have to be mixed with the limey ores of the Lincoln district. I need not take up much time on this matter, as Dr. Colclough has already told us that we should derive little if any benefit from the use of an acid slag in this district.

Fourthly, let us take an ore burden in which the ores are of such a high sulphur content that you are bound to run with a slag volume which is sufficiently high, where the sulphur saturation of the slag will be over 2% and the sulphur content in the iron is up to its high limit from the point of view of supplying it to a steel plant; here I may say that I am taking into account the crushing, screening and sintering of the Northampton ores. In this case you cannot adopt the acid burden, as the slag is already saturated with sulphur, and any excess would normally be absorbed in your iron, or cause great derangement in your furnace hearth,

and a great part of the iron would be carried in a kind of mechanical mixture along with the slag, causing a shoddy iron, with a corresponding loss of iron with the slag and naturally a loss in output and higher fuel consumption.

I should like to emphasise that not only is the physical treatment of the ores essential, but attention must also be paid to the chemical characteristics, so far as the sulphur content is concerned. This also applies to the sulphur content of the coke. The presence of sulphur in our ores and coke is very important, and the fact is often overlooked that it is due to this cause that high slag volumes have to be maintained with a high CaO/SiO_2 ratio along with high hearth temperatures to carry the sulphur in the burden. In my opinion it is impossible to work a furnace on an acid slag under such conditions, the total result being that we can only expect to have higher coke consumptions. In this respect I quite agree with Dr. Colclough that the principles of acid burdening to bring about lower fuel consumptions cannot be universally applied.

REFRACTORIES.

(Second day, morning session, continued.)

Dr. J. H. CHESTERS (Central Research Department, The United Steel Companies, Ltd., Stocksbridge), in presenting this subject for discussion, said : There are two aspects of the question of refractories on which I want to touch. The first is the question of variability, the brick-to-brick variation ; the second is carbon bricks, about which we heard something in the earlier discussion yesterday.

The variability of bricks is one of the facts of nature ; it is not a question of the negligence of the manufacturer. When the crushing strength of a batch of firebricks is determined there is always a spread, and this is the crux of the whole problem of specifications. When in the past we said that bricks should not crush below, say, 5000 lb. per sq. in., did we really mean that or did we mean that the average must be 5000 lb. per sq. in. ? The two things are very different. Suppose that we specify that the average strength of the bricks should be 7000 lb. per sq. in. ; the maker will do his best, but the strength of quite a lot of those bricks will be below 5000 lb., and of an odd one here and there it may be as low as 2000 lb. per sq. in.

Fortunately the variation is less when we come to other properties such as bulk density, but it does mean that we must change our ideas about specifications if we are going to apply them to bricks.

There are two approaches to the problem as I see it. The first, which is every-day practice, is to base our requirements on what was achieved with previous batches ; a comparison of the histograms of the properties of the old and new batches shows whether the new bricks are better or worse than the old ones. A decision cannot be based on only one brick, however ; at least twenty are required.

An example is provided in Table LIX. of the Report ; the test results show that the variation of crushing strength due to weathering for two years is negligible in comparison with the variation between the individual bricks received in a given consignment.

The other method of approach, which I commend to the serious consideration of the Blast-Furnace Refractories Panel, is the use of specifications of the type which provides that a consignment of bricks (for, say, a stack) should have an average crushing strength of over, say, 4000 lb. per sq. in., and that for not more than 20% of those bricks should it be less than 3000 lb. This may horrify the purchasing departments, but it

is much more scientific and would be the first step towards the development of a specification for blast-furnace bricks which really meant something.

With regard to carbon bricks, there is an interesting story behind the investigations recorded in Section V. Our success in improving on German achievements (*see* Table LXIII.) prompted us to seek the collaboration of a brick-maker. He made 200 bricks for us. They were put into a furnace two and a half years ago; they came to light only a week or so ago and only about ½ in. was worn off them. But a wait of two and a half years meant slow progress, so it was decided that a brick-making plant must be built, and two firms undertook this between them. We came into the scheme with our quality control, and for the first time in our history we decided what the bricks were going to be like *before* we made them. We specified a crushing strength of 5000 lb. per sq. in. (not on every brick, of course, but on most of them), a bulk density of 1·50 g. per c.c. and certain other properties; after some time the bricks began to come off the line, and, to our amazement and satisfaction, they were above specification.

So far as properties are concerned, I would give priority to a high thermal conductivity. It has been said that the best refractory is water; the fuel engineer may object, and rightly (I think that fuel costs and refractory costs should be added). It is, however, a fact that if water-cooling can be applied, the attack on and penetration of refractories can be reduced. The conductivity of the carbon bricks was about 15 B.Th.U. per sq. ft. per hr. per °F. per in. as compared with about 5 B.Th.U. for fireclay. We hoped, therefore, to be able to chill the iron three times as far away from the outside of the case with carbon bricks. Apart from this consideration they have a remarkable resistance to slag and molten iron.

Another question was whether these carbon bricks were volume-stable; the shrinkage, to which Dr. Rigby referred yesterday, is liable, I agree, to be a menace and may be the cause of a breakout. Ordinary shrinkage tests (which have to be done in a reducing atmosphere to avoid burning the brick) were carried out not only at 1500° C., giving a value of 1% after 2 hr., but also at 2000° C., at which temperature the shrinkage was 2·5%. It gives us a great deal of confidence to know that if ever the temperature of a blast-furnace is raised to 2000° C. (this will not be for many years, I hope) the shrinkage will be no more than 2½%. The sort of shrinkage that Dr. Rigby was talking about was that of a brick of which the porosity decreased from 25% to nil; that means an 8% linear shrinkage, and would probably refer to a temperature of about 1500° C.

The hot strength of these carbon bricks is remarkable; at blast-furnace temperatures (round about 1470° C.) they will withstand, not merely 50 lb. per sq. in. (the usual under-load figure), but over 2 tons per sq. in. I feel, therefore, that these bricks really will do all that we want, provided that oxygen is kept away from them.

Col. ALAN STEIN, M.C. (Messrs. John G. Stein & Co., Ltd., Bonny-bridge) : I find Sections V. and VI. of the Report very interesting, and, like the rest of the Report, very practical. There is one point mentioned in Section V., which has been referred to by Dr. Chesters, on which I should like to comment, namely, the German specification. The crushing strength given there, I would point out, is determined on a small cylinder which, while it is not specified, is in fact cut on the flat way of the brick. That is the way the brick is pressed while it is being made. In the figures given in the Tables in the Report, on the other hand, the strength is taken on end. That is quite clearly stated, but the point is that the

difference between these two ways may be of the order of 100%, so that that should be kept in mind.

Another point concerns the porosity. The figures given in the German paper are for the total or true porosity, whereas the figures given in Section V., although it does not say so, are all " apparent " porosities. Later in Section VI., in Table LXVII., the term " apparent " porosity is correctly used, but that is not done everywhere, and my view is that we should not quote figures for " porosity " at all, because it leads to confusion. We should refer to the true or total porosity on the one hand or to the apparent porosity on the other. All the figures published for porosities in America are really the apparent porosities.

I mention these two points so that we may have a clear picture of what we are talking about when we refer to these two properties. I do not want it to be thought that we should not strive to improve all the properties of the British refractories, and I am certain that this excellent Report will be a great stimulus to British makers to improve their refractories in every respect, and especially in regard to strength and low porosity.

The next point that I want to make is with regard to slag attack. It is stated that tests were made on bricks of much higher alumina content, and that these offered much greater resistance to corrosion by iron oxide, but not by blast-furnace slag. No figures are given to substantiate that last remark, and I can only say that it does not agree with my own experience and with what I should expect on theoretical grounds. I think that that has some importance when we come to consider the possible use in selected places of really high-alumina bricks, say, 70% alumina or over.

The trials made with carbon bricks are very interesting and promising, but I suggest that with the results already achieved in Britain and in America with the 42% alumina brick, and with the improvements in design suggested in Section X. of this Report, which deals with hearth breakouts, we shall be able to get satisfactory results in almost all cases. In the exceptional case (and Appleby-Frodingham is admittedly one) where there is this very fluid iron, my suggestion is that as an alternative to carbon in the particular parts that give trouble the 70% alumina brick (70% or over) should be used. It has the following advantages over the 42% alumina brick : Much higher refractoriness, and much higher refractoriness-under-load ; the latter would be about 100° C. higher in the under-load test at 28 lb. per sq. in. It also has the advantage of lower after-contraction. I would also emphasise that it has much better resistance to ferrous oxide and, I maintain, to blast-furnace slag. For all these reasons I think that this brick is a very good alternative to the carbon brick, and there is no risk of it going up in smoke should air unfortunately have access to it.

Section VI. makes a good case for the use of cleaned gas, and the points made with regard to design are very helpful.

Dr. D. F. MARSHALL (The Park Gate Iron and Steel Co., Ltd., Rotherham): In November, 1942, we reported to the Eighth Blast-Furnace Conference of the British Iron and Steel Federation our experiences of refractories used in stoves running with dome temperatures of 1200° C., heating the blast to 750–800° C. Two general conclusions were drawn from that report, namely :

(a) Even with modern gas-cleaning equipment, conditions may occur in a stove which are conducive to the vitrification and contraction of brickwork. It was suggested that these conditions resulted from the presence of alkali fumes or dust at high temperatures. In

PLATE XXVIII.

Fig. F.—Firebricks after 12 Months in Blast-Furnace Stove.
(*See* D. F. Marshall's contribution.)

PLATE XXIX.

FIG. G.—Firebrick No. 5 after 12 Months in Blast-Furnace Stove.

FIG. H.—Semi-Silica Bricks after 12 Months in Blast-Furnace Stove.
(*See* D. F. Marshall's contribution.)

this connection it has been suggested in America [1] that the higher the degree of gas cleaning the more alkaline does the residual dust become.

(b) Bricks with a high alkali content and finely ground grog failed under these conditions, whereas siliceous bricks produced from more coarsely ground material withstood the attack much better.

Since reporting these works observations the problem has been tackled in two ways. First, all sections of vitrified, contracted and distorted bricks were removed from the stoves and replaced by $9 \times 4\frac{1}{2} \times 3$-in. common firebricks produced from South Yorkshire clays. Up to the present time the results have been very satisfactory. Examination of replacements after 12 months' operation showed slight surface glazing with no distortion of the general checker arrangement.

Secondly, eight different types of bricks were put on the fender wall of a stove, each being supported on tiles at the ends only. After 18 months' continuous stove operation the test bricks were removed and analyses made on samples from the face and the centre of each brick. Figs. F, G and H, photographs of the test bricks, indicate clearly that only one brick, No. 5, softened enough to distort. Samples No. 1, 2 and 6 show a few cracks of the spalling type, which might reasonably be expected from bricks of this semi-silica sand type.

Table B, giving the analyses of the samples, shows two consistent features, in that all the face samples are higher in alkali and zinc oxide content than samples from the centre of the brick. It seems very probable, therefore, that these are the two main factors producing brick vitrification. One further interesting feature is that, whilst the semi-silica brick with a high alkali content (No. 1) suffered no deformation, brick No. 5 with a much lower silica content but a high alkali content shows

[1] O. R. Rice, *Iron and Steel Engineer*, 1942, vol. 19, Dec., p. 66.

TABLE B.—*Analyses of Bricks after 18 Months in a Blast-Furnace Stove.*

Brick No.		Semi-Silica Bricks						Firebricks									
		1.		2.		6.		3.		4.		5.		7.		8.
	%	Centre.	Surface.	Centre.	Surface.	Centre.	Surface.	Centre.	Surface.	Centre.	Surface.	Centre.	Surface.	Centre.	Surface.	Centre.	Surface.
SiO_2		90·4	87·2	90·2	87·0	90·8	86·8	63·6	58·6	58·6	59·4	55·00	54·2	61·2	60·00	57·80	57·40
Al_2O_3		6·55	7·66	7·12	5·77	6·10	5·82	30·72	32·94	32·10	31·81	36·10	34·9	28·75	29·30	32·60	33·20
Fe_2O_3		0·86	0·86	1·43	1·71	1·71	1·43	2·86	2·86	5·71	5·71	4·30	4·6	6·29	5·71	6·00	5·44
CaO		Trace	Trace	Trace	Trace	Trace	Trace	0·20	0·40	0·50	0·30	Nil	Nil	0·20	0·30	0·10	0·20
MgO		0·06	0·08	0·36	0·43	0·36	0·36	0·65	0·72	0·94	0·87	1·70	2·20	1·30	1·44	1·59	1·59
TiO_2		0·31	0·25	0·25	0·30	0·33	0·38	1·20	1·33	1·50	1·33	1·00	1·10	1·32	1·24	1·90	0·85
ZnO		Trace	2·19	Nil	1·80	Nil	3·40	Nil	1·82	Nil	0·54	N.D.*	N.D.*	Nil	0·84	Nil	0·32
Alkali.		1·09	1·33	0·44	1·17	0·37	1·22	0·47	0·72	0·47	0·53	1·20	2·10	0·47	0·53	0·47	0·47

* Not determined.

most deformation. The answer probably lies in the relative amounts of glass present in the original bricks.

Summarising the position, we may say : (1) Even with a modern gas-cleaning plant, conditions may be set up in a blast-furnace stove which are conducive to a high degree of brick vitrification. In some cases this may distort the checkers. (2) There is some evidence that the presence of alkalis and zinc oxide at high temperatures (1200° C.) produces this vitrification. (3) Siliceous firebricks with a fairly coarse grog and a low alkali content are more resistant to these conditions than other types of brick.

Finally, on p. 156 of Special Report No. 30 doubts are expressed as to the value of elaborate shapes for checkering stoves, particularly when zoning is used. Designs which follow this principle presuppose that no further attention will be required once the stove comes into operation. If, as in the case reported, this supposition is incorrect, then zoning can be dangerous, since it becomes impossible to clean out debris produced during repairs.

Dr. W. J. REES (Sheffield University) : I should like to correct the impression which may be given by the opening paragraph of Section V. of Mr. Elliot's Report, that workers in the refractory field tended to consider work on blast-furnace refractories one of the less important jobs. Believe me, this is not the case. Quite a number of investigators in refractories technology have been active in this field for at least the last twenty years, and the good results which Dr. Chesters details in this Report are in no small measure due to that earlier work, which was carried out very largely under the auspices of the Blast-Furnace Refractories Joint Committee, and later by the Blast-Furnace Refractories Panel. I should like to put it in this way, that in this work the authors have added some useful courses to a structure which had already been to some extent built, and that in their work on carbon blocks they have gone further than that and have added a very useful annex to the building.

The results which Dr. Chesters details could not have been obtained if a good deal of progress had not already been achieved by both the technologists and the brick-makers in improving the general quality of blast-furnace and stove refractories. I would refer, for example, to that part of the Report which deals with the weathering of bricks, because that proves the point which I am trying to make. If those weathering tests had been made on bricks produced fifteen or twenty years ago, then the results would have been very different. Bricks which are properly burnt are more resistant to weathering than bricks that are underburnt. That point is brought out in the Report, but the majority of blast-furnace bricks available to-day are pretty well burnt, and in consequence do not deteriorate very much on exposure to the weather. Nevertheless, I should deprecate very strongly the deduction being drawn from this part of the Report that it is safe to stock blast-furnace or stove refractories in the open. It is a most dangerous thing to do, because, although the tests reported here do not show any marked deterioration in the quality of the bricks, there is some deterioration even in well-burnt bricks if they are exposed to the weather conditions which we are apt to get in Britain. I emphasise that very strongly. If either makers or users have to stock blast-furnace refractories, let them be stocked under good conditions, protected from the weather, and then they will be safe.

Colonel Stein has already drawn attention to one point on which I wish to say a word. I agree with him, from my own tests carried out over many years, that the more aluminous refractories are more resistant to corrosion by basic slag than the medium-alumina bricks. The rate of

increase of resistance is not quite so rapid as it is with, say, iron oxide pills, but I should be very definite in the deduction from my own tests that the aluminous refractories in the region of, say, 50–70% are definitely resistant to corrosion by basic slag. The type of refractory to which I referred in the previous discussion, the fusion-cast refractory, which can be made in all compositions from, say, 60% alumina up to 100% alumina, is highly resistant to corrosion by basic slag. I would add here that that type of refractory is attracting a good deal of attention in metallurgical circles in America at the present time, and one large company already has plant for the commercial production of fusion-cast refractories for the iron and steel industries. Trials have been made and, I understand, they have given very satisfactory results.

I am completely at one with the authors in their comments on stove refractories, and it is gratifying to me to find a blast-furnace technologist admitting that even in clean gas you do get alkalis. I have been told once or twice, when I have ventured to suggest that perhaps the bricks had absorbed some alkali, that I could dismiss that at once; it was quite impossible, as they were using clean gas. From " clean-gas " stoves I have examined bricks where the alkali had gone up from an initial $1\frac{1}{2}\%$ to $3\frac{1}{2}\%$, with a corresponding change in the character of the brick.

I agree with the conclusions of the authors on the behaviour of the type of brick which tends to bloat. That is sound from both theoretical and practical considerations. The changes in character of the brick will be less serious with the siliceous brick than with the moderately aluminous brick which contains 3% or 4% of fluxing impurities in the natural clay.

From my contacts with the makers of refractories, I can speak very highly of their great endeavours in the last fifteen to twenty years to improve the quality of the bricks supplied to ironmakers for blast-furnaces. The majority of makers of this type of refractory are now producing bricks with a reasonably good crushing strength and which are reasonably uniform, well burnt and of good shape and finish, so that they can be built together practically without any jointing cement. They would certainly comply in general with the German specification, if one makes the proviso referred to by Colonel Stein with regard to the way in which the samples are taken. Great progress has been made in the application of grading of the clays and of vacuum pressing, vacuum extrusion and so on, so as to secure the maximum density, the lowest porosity and the lowest permeability, and the improvement is seen in the very much improved results under strenuous conditions which are being obtained from blast-furnaces in various parts of the country.

I should like to say a word with regard to blast-furnace cements, because even with these very well made blast-furnace bricks some cement is necessary. Reference is made to carbon deposition, and it is stated that after a blast-furnace has been blown out one invariably does find that, even when the bricks remain perfectly sound, the joints are black from carbon deposition. That is due, in my opinion, to the fact that in the fine grinding of the cement there is some contamination with metallic iron from the grinding plant. It would be an advantage—I do not know whether it is feasible on the production scale, but I see no reason why it should not be—if blast-furnace cements were passed through a magnetic separator after grinding in order to eliminate the metallic-iron contamination, for it can be serious if it gets high, because with this deposition of carbon within the joint there is some swelling of the joint, and pressure develops which can lead to stress in the bricks.

Mr. A. T. Green (British Refractories Research Association, Stoke-on-Trent) : I welcome Mr. Elliot's Report as an important contribution to

the study of blast-furnace linings; the results now published form a useful addition to the data collected over many years by the Joint Committee of the Iron and Steel Industrial Council and the B.R.R.A. There are a few points on which I would like to comment. In the first place, examination of upwards of a hundred blown-out linings has served to emphasise the fact that at many blast-furnaces in Britain a major part of the trouble has been the disintegration of the lining by carbon monoxide. I therefore feel that it would be a definite advantage to test all refractory materials intended for use in the stack of a blast-furnace for resistance to disintegration by this gas. Even when a refractory material is found to resist carbon monoxide in the laboratory test as normally carried out, reactions could occur in the blast-furnace which might render the brick susceptible to attack; this feature is being investigated at the Mellor Laboratories. I emphasise this cause of breakdown of blast-furnace linings, because in my experience it is the most common source of failure in Great Britain.

I would not agree with the suggestion in the Report that the cold crushing strength of a brick should be a major consideration in the selection of a blast-furnace refractory. However, perhaps this is not the meaning intended by the authors.

Turning to the question of stove fillings, I can confirm that a concentration of alkalis is frequently present in the used bricks; as much as 4–5% of alkali has been found by analysis. The B.R.R.A. has spent much time in the study of the influence of alkalis on refractory materials. Varying effects were observed, depending on the temperature and the nature of the brick. In some cases actual recrystallisation of certain types of alkali salts could take place, while in other cases increased vitrification of the brick occurred. While it remains difficult to forecast in detail the course of the reaction in any particular case, I believe that sufficient data are now available to give good guidance in determining what reactions are likely to occur in a hot-blast stove. In addition to resistance to alkali attack, a major feature of stove fillings must be that the refractory material is non-contractile during use.

I am interested in that sub-section of the Report which deals with the use of carbon bricks in blast-furnace hearths. Some initial experiments on the production of bricks of this type were carried out four or five years ago at the Mellor Laboratories. Even in this preliminary work, before experience had been gained and before this type of refractory had become more fully developed in Britain, a brick was produced which would withstand a load of 50 lb. per sq. in. at a temperature of over 1700° C. in a reducing atmosphere.

Mr. W. G. GIRLING (Messrs. Henry Foster & Co., Ltd., Newcastle-on-Tyne) : There are one or two questions which I should like to put to Dr. Chesters. First of all, with regard to hot-blast stoves and what is stated on p. 157 of the Report, is it the view of the Appleby-Frodingham Company that zoned checkers are unnecessary if zoning is achieved by complicated brick shapes ? I am not clear what that sentence means. Does it mean that zoning should not be indulged in if it can be accomplished only by a complicated checker ?

I am glad to see that particular reference has been made to the construction of the brickwork in stoves, because, as we all know, the working conditions in hot-blast stoves with clean gas are severe, and the brickwork itself is now a matter of very great importance. In conference with certain of the ironworks there has been considerable discussion of the question of the circular as compared with the elliptical combustion chamber. I hesitate, as a brickmaker, to give my views, but, judging

from the stoves seen after service, and having regard to the reactions which take place in the stove, I feel that there are several arguments in favour of the independent circular combustion chamber built separately from the shell, thereby allowing free expansion, as compared with the elliptical chamber brickwork bonded into the main shell brickwork, causing unequal expansion.

On p. 161 of the Report the conclusion is reached that under the conditions specified there " bricks with a tendency to bloat on refiring are preferable to those with a tendency to shrink." Is it the opinion at Appleby-Frodingham that, in the light of present-day knowledge, they would definitely prefer to have on all occasions this brick with bloating qualities rather than a really well-fired high-aluminous brick with low after-contraction ?

Reference has been made to outputs in Germany and in America. Unfortunately, owing to the war, we do not know so much about conditions in America, not to mention Germany, as we did before the war, but as far as furnace outputs per lining in Britain are concerned a considerable number have given and are giving an iron output per lining very much larger than has ever been obtained in the past, and with a very much greater throughput, owing to the nature of the ores which have to be employed in certain parts of the country as a result of war conditions. I think, therefore, that these factors should be borne in mind. I am not suggesting that the blast-furnace linings which are being manufactured to-day, although greatly improved, are entitled to all the credit ; there are other factors, such as water-cooling, &c., which have made their contribution.

CORRESPONDENCE.

Mr. D. F. CAMPBELL (Messrs. Campbell and Gifford, Ltd., Weybridge) wrote : Dr. Colclough refers to the advisability of research into the beneficiation of British ores by magnetic separation after roasting. If an investigation is made, the use of a hysteretic electrical field would also be well worth consideration. This repels not only ordinary magnetic minerals, such as magnetite, but also specular hematite and other material which does not readily respond to magnetic separation.

Hysteresis also provides a field which is much more favourable for mineral separation, as its intensity is effective over a greater distance from the electrical apparatus than is the case with magnetic separators. Consequently, a thicker stream of mineral can be passed over a separator of given size.

The use of this system of separation is only in an early state of development, but is certainly worth consideration by investigators on the beneficiation of iron ores.

Dr. J. H. TAYLOR (Geological Survey and Museum, London) wrote : Much of the information accumulating in the laboratories of the iron and steel companies regarding such characteristics of the sedimentary iron ores as porosity, reducibility and thermal conductivity suffers from the disadvantage of not being related to particular types of ore. In many cases it is, indeed, impossible to discover the nature of the ore that has been tested. Frequently only a brief description such as " compact brown ironstone " or " hard grey-green ironstone " is available. From such meagre information, together with a chemical analysis, one has to try to deduce the character of the original sample.

Chemical analyses by themselves do not provide adequate evidence on which to identify an ore type and leave considerable gaps in our knowledge of the composition of the ore. For example, while the total silica content is recorded, there is no indication of the state in which the silica occurs. Part of it may be free silica in the form of sand grains, part combined in a clay mineral, part present in the iron alumino-silicate chamosite. Similarly, a percentage for sulphur in an analysis gives no information as to the proportion present as a sulphide in the form of pyrites or as a sulphate in the form of gypsum.

Clearly such factors as the mineral composition of the ore together with its texture and grain size must have an important bearing, not only on the behaviour of the ore in the furnace, but also on the processes to be employed in the preparation of the furnace burden. The necessary information can be supplied only by a detailed petrographical examination under the microscope, and it is essential that such an examination should in future be made to supplement all chemical and physical tests which are carried out.

By his remarks during the discussion Dr. Groves may have inadvertently given the impression that within recent years little petrological work has been done on the Jurassic iron ores. This, of course, is far from being the case. A detailed study of the Jurassic ironstone fields has been included in the war-time programme of the Geological Survey, and petrological investigation has formed part of this work. In, for example, the Northampton ironstone, which has so far received the most detailed study by the Survey, it has been found possible, despite the extreme variability of the ore and the complications introduced by weathering, to recognise a number of ore types which are of fairly wide distribution. For each of these types such characteristics as mineral composition, texture and average chemical composition are known. It is hoped that these results (to be published in forthcoming *Memoirs of the Geological Survey*) will provide a scientific and practical basis for further work and that it will be possible to assign any samples of ironstone of which the physical characteristics are studied to one or other of the standard ore types. The ultimate goal should be the establishment of a correlation between petrological, chemical and physical data so close that, once an ore has been assigned to its correct type, its suitability for various ore-dressing processes and its probable behaviour in the furnace can be inferred.

Mr. STANLEY GARSON (late of Messrs. Gjers Mills & Co., Ltd., Middlesbrough) wrote : The Report by Mr. Elliot and his collaborators will be a valuable work for future reference ; it requires weeks of study.

Section VII., Scaffolds.—Would it have been possible to handle the scaffold in No. 6 furnace by means of coke—to have stopped charging burden and put in coke only ? The writer has cleared a chimney scaffold on one occasion and side scaffolds on others by charging coke alone.

Section XI., Lifting of the Blast-Furnace Superstructure.—About forty years ago at a Tees-side plant, cast-iron flange plates had been built into the brickwork at the furnace top to prevent abrasion. The flanges of the plates were inside the furnace and 4 in. deep. In a short time the furnace top began to rise and the plates were taken out, but this is the first occasion I have known of mild-steel plates causing a rise of superstructure.

Section X., Hearth Breakouts.—On two occasions and at two separate furnaces the furnace burdens were changed from a normal hematite iron to one with silicon 1–1½%, phosphorus 0·05% and manganese 2–3%. Within a fortnight the iron made was passing into the bottom and none from the tapping hole, only slag. The blast was taken off for 24 hr. and water

applied; no further trouble was experienced. Could this trouble have been due to the high percentage of manganese ?

Mr. P. WALKER (Cargo Fleet Iron Co., Ltd., Middlesbrough) wrote : The introductory remarks of Mr. Baxter and the late Dr. Swinden have been perused with interest, and they have done well to emphasise the statement of Mr. Henderson as to the necessity for research to be directed to the practical desire to improve the quality and profitably modify the processes of making pig iron. Their plea for the necessity of sharing experience in pig-iron manufacture is deserving of consideration and subsequent action in furtherance of the promotion of a closer degree of mutual collaboration amongst producers of pig iron.

I would like to refer to the recoking experiments described on pp. 101–108 of Mr. Elliot's Report. The results are very interesting. Calculated to a weight basis, the combustible gases evolved at 750° C. are lower and those evolved at 1000° C. are appreciably higher than the amounts obtained by the normal method of volatile-matter determination at a temperature of 925° C. The results seem to indicate that some modification is desirable in the general view, which tends to look upon the fixed-carbon content of the coke as the whole medium in the reduction process of the blast-furnace.

It is noted that coke No. 4 and, to a less extent, coke No. 2 gave volumes of nitrogen in excess of that usually associated with British coals. The inference of the authors that a higher-volatile coke will have a greater reactivity from a reduction point of view at temperatures above 1000° C. would appear to be justified by the results of their reduction experiments. As they state, the chief problem with a high volatile content in coke is the maintenance of satisfactory physical properties. Our experience with coke made from Durham coals is that a volatile content of up to 1·90% at 925° C. does not significantly affect the physical properties as indicated by the results of the shatter test, the Cochrane abrasion test and the Micum test. In addition, no deterioration in the smoothness of driving of the blast-furnaces nor increase in coke consumption has taken place.

In reference to ore preparation in the Appleby-Frodingham Report, the developments outlined with such a variable ore as that from the Frodingham bed are most interesting, particularly those relating to the bedding plant. When considering the wide range in chemical analysis shown by this ore, the results obtained from this bedding plant are excellent. As one concerned with obtaining representative samples of a variable Northampton ironstone, I should appreciate a description of the sampling procedure in operating the bedding plant.

The description of the ore-drying plant for Northampton ore and the particulars of the furnace operating results when using semi-dried ore are noted. An increase in pig-iron output to the extent of 210 tons per week plus a reduction of 1·40 cwt. of coke per ton of iron is definitely valuable. If, as concluded, these results are solely due to the removal of part of the moisture from the Northampton ironstone, the question arises whether the results here given could be improved upon by a further reduction in moisture content.

In this respect, the author's remarks on p. 229 relative to the dissociation of water by impregnated carbon are to be noted, as they draw attention to a direct loss in carbon as a result of this possible reaction.

Dr. Colclough's paper emphasises clearly the economies which can be obtained in coke consumption and the important part which is played by ore preparation in bringing about the desired improvement. The paper has been read particularly in reference to the results obtained by crushing and sintering, p. 371 P, and to the results given by Mr. Elliot

concerning dried Northampton ironstone, period 1, p. 28 and the remarks·
on pp. 230–231 of his Report. Perusal of these data shows that in actual
practice at Appleby-Frodingham the figures given by Dr. Colclough for
coke economies have been largely achieved. It is, however, noted that
the CO/CO_2 ratio at Appleby-Frodingham is $3:1$, as against Dr. Col-
clough's objective of $1.86:1$. Examination of the operating data does
not provide an explanation for the difference, and it would appear that
the reasons given by Mr. Elliot, namely, that extra coke has to be used
on account of the high slag volume (which, by the way, is similar in
amount to that given in Dr. Colclough's example), long fusion zone and
high bulk ratio of ore to coke are to be largely accepted, and that atten-
tion to furnace design may improve their coke consumption and, as a
result, reduce the CO/CO_2 ratio. This being so, it is of the highest im-
portance in future furnace construction that the closest attention be paid
to all aspects of design, in order that the fullest advantage may be obtained
in coke economy.

Dr. J. TAYLOR (British Iron and Steel Federation, London) wrote : In
Section XI. of their very fine Report Mr. Elliot and his associates record a
phenomenon in which I am interested. I refer to the voluminous carbon
deposition on the armouring bars in the upper part of the stack. Refer-
ence is made to a paper by Baukloh and Henke, in which it is stated that
metallic iron is the active catalytic agent for the carbon-deposition
reaction. This does not accord with experimental results that I have
obtained. What the catalyst is is not certain, but in my opinion the
presence of ferroso-ferric oxide (Fe_3O_4) is essential. It may be that the
reaction proceeds at an Fe/Fe_3O_4 interface, but this is only speculation.
In this connection it should be remembered that the composition of
the gas phase is not a reliable guide to the reaction equilibrium on the
catalyst surface, on which the adsorbed gas layer may differ widely
in composition from the main body of the gas. For instance, carbon
deposition can occur if pure iron powder is treated with pure carbon
monoxide at 550° C., but even when the carbon dioxide in the exit gas is
less than 0.5%, Fe_3O_4 is found in the product.

In my experience carbon deposition occurs much more readily on iron
oxide than on massive steel. This is because in the former case the catalyst
is more readily dispersed in the depositing carbon and so presents a greater
catalytic surface. I suggest that if oxide scale and rust are prevented,
the trouble should be largely, if not completely, eliminated. Practical
steps to this end which suggest themselves are :

(1) Thorough descaling.
(2) Painting with an anti-corrosion paint, such as aluminium
paint, to prevent rusting in the interval between the placing of the
bars and the blowing-in of the furnace. High-temperature paints
with a sodium silicate base should be avoided, as there is evidence
that soda has an accelerating influence on the reaction.
(3) Calorising the bars, if practicable, would, I think, be a most
effective preventive.

There are also one or two points in Section IX. which call for comment.
The importance attached to the 700° C. isotherm appears to me exaggerated.
Surely there is little chance of direct reduction below 900° C. The CO/CO_2
equilibrium value over coke at 900° C. is CO_2 3.4%, CO 96.6%, or, on the
basis of 60% nitrogen, CO_2 1.4%, CO 38.6%. Average gas analyses
for a Frodingham furnace at the 900° C. isotherm were CO_2 1.0%, CO
36.5%, CH_4 0.5%, hydrogen 1.1% and nitrogen 60.9%,[1] and similar

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[1] *The Iron and Steel Institute*, 1937, *Special Report No.* 18.

figures for the furnace investigated at Skinningrove were CO_2 1·3%, CO 39·0%, hydrogen 1·1% and nitrogen 59·7%.[1]

Then, in discussing the effect of moisture in the burden it is stated that the dissociation of the liberated moisture is through reaction with carbon. Why should carbon be necessary? The reaction $CO + H_2O \rightleftharpoons CO_2 + H_2$ on an iron catalyst at about 600° C. is a well-known industrial reaction.

There is also some confusion as to why such moisture adversely affects blast-furnace operation. In Section II. it is ascribed to wet sticky ores worsening the distribution, whilst in Section IX. it is ascribed to the gasification of deposited carbon by water vapour, with consequent loss of carbon from the furnace. It is more probable that the moisture only reacts with the carbon monoxide as shown above. The figures given then only indicate a slight worsening of the reducing power of the gas. For the high CO/CO_2 top-gas ratio at Frodingham this should be unimportant.

The deleterious effect of the moisture is more probably physical. Increasing moisture results in :

(1) Poorer distribution.

(2) Slower heating of the burden and consequent shorter effective ore reduction time. This will be most pronounced with large ore pieces.

(3) Extension of the lower temperature zone further down the furnace. This increases the region in which carbon deposition can occur, with the consequent risk of hanging.

Dr. STACEY G. WARD (University of Birmingham) wrote : In Section VII. of Mr. Elliot's Report the most important sentence is, in my submission, the first sentence in the summary (p. 166) : "The furnace manager is handicapped by the lack of fundamental knowledge of the process." How can a furnace manager ever hope to achieve the real efficiency and smooth working of the furnace which is his ultimate aim, or to cope with the legion of variables, if the fundamental knowledge of the process is imperfect ? I wish to support the plea made in Section VII. for more extensive organised research on blast-furnace processes, including work on models. The blast-furnace has for too long been the Cinderella of iron and steel works plant.

In that part of the Section on stock distribution the desirability of an M-stockline at Appleby-Frodingham is indicated, and it is stated that the success so often attendant upon the lowering of the stockline to secure easier movement of stock is undoubtedly due to the different effects of a V- and an M-stockline. This fact was well demonstrated on the North-East Coast furnace which was the subject of field-tests similar to those carried out on the Frodingham No. 1 furnace. It was found that the North-East Coast furnace was sluggish and very prone to hanging when the stockline was normal, and it was shown that under such conditions the stockline was of V-formation. If, however, the stockline was maintained a few feet below normal the furnace ran, to use the furnacemen's own term, like wild-fire ; temperatures and gas sampling tests across the stack showed that under good running conditions the stockline was of M-formation.

On p. 214, Section VIII., reference is made to the presence of KCN in and near the scaffold which was so successfully removed. I can sympathise with the lance operators who complained of sore lips and sickness. When sampling from the stack of Frodingham No. 1 furnace during the field tests reported in The Iron and Steel Institute's *Special Report No.* 18, just

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[1] Results of an unpublished investigation by the Blast-Furnace Committee of the British Iron and Steel Federation.

above the bosh a scab 2 ft. thick was encountered. On driving a sampling hole through the scab a white fume containing KCN was produced, causing skinning of the lips and sickness; the joint effect of mild KCN poisoning and mild CO poisoning is to produce an apathetic lassitude which lasts for two or three days.

I should like to express my admiration of the way in which the task of removing the scaffold from No. 6 furnace was tackled and completed. The theory suggested for scaffold formation appears to be quite sound and fits the facts, but, as shown by Bone and his co-workers, the rate of reduction of iron oxides slows up at about 700° C., and this may influence scaffold formation. More information is required about what happens in the furnace at about 700° C.

Mr. J. H. PATCHETT (Messrs Dorman Long & Co., Ltd., Middlesbrough) wrote : With regard to the information given in Mr. Elliot's Report on furnace breakouts, there appear to be two outstanding conditions contributing to the cause of them at Appleby :

(a) The position of the tapping hole in relation to the slag notches, which appears to be recognised by the Appleby management in view of the statement on p. 83.

(b) Lack of sufficient cooling, to which cause most breakouts can be attributed.

I cannot subscribe to the theory that the penetration of oxygen into the hearth brickwork is the cause of the breakouts. It may have a contributory effect, but this can be overcome with more efficient cooling.

It is suggested that cooling pipes, of $2\frac{3}{4}$-in. bore and $\frac{3}{8}$ in. in thickness, be installed and fed with water either into an internal pipe of $1\frac{1}{4}$-in. bore or two pipes coupled together in the form of a U-pipe and fed into one leg, these pipes to be set close together inside the hearth jacket and bedded in coke-and-tar ramming. This will give more efficient cooling to the hearth than the cooling staves generally in use. This method of cooling has been tried over a period of 14 years on a number of furnaces, with no breakout having taken place through the cooling pipes. No doubt the adoption of a carbon-brick hearth will be less liable to allow iron penetration than any form of firebrick, but it is considered that with more efficient cooling a carbon hearth may not be necessary.

Mr. R. A. HACKING (Messrs. Dorman Long & Co., Ltd., Middlesbrough) wrote : Dr. Colclough's principal theme is that uniformity of chemical, thermal and physical conditions is the key to more economical blast-furnace practice, and that all practicable steps should be taken to this end.

In the case of furnaces using lean British ores charged in the as-quarried condition, I suggest that the proportion of fuel expended in correcting swings in operating conditions, with the emphasis upon the hearth, would be truly alarming if one could gauge it accurately. I also put forward the suggestion that, under such operating conditions, variations in iron and slag analyses and temperature are due less to direct chemical upset of the burdening scheme than to serious interruptions and irregularities in gas distribution and stock descent. Changes in practice which contribute towards minimising these irregularities cannot but be beneficial to fuel economy. In the interests of uniformity, one is able sometimes to improve results by introducing factors which theoretically appear to be opposed to fuel economy. The classic example is the use of lower blast temperatures, which, in innumerable instances, particularly when using home ores, have reduced coke consumption, obviously by achieving smoother

descent of the stock, reducing variations in gas flow over its cross-section, &c.

A second example is provided by recent experiments at Corrigan-McKinney No. 4 furnace,[1] where steam injections, automatically regulated to give blast of constant moisture content, achieved the main object of better control of the silicon content of the iron, without increasing, and in some periods even reducing, the coke consumption.

Herein also, in my opinion, lies the chief virtue of the big furnace. I well recall some three years ago Mr. Elliot's stressing of this point, as demonstrated by the following units working on identical burdens :

Hearth diameter .	.	.	.	11 ft. 0 in.	17 ft. 0 in.	22 ft. 0 in.
Coke consumption.	Per ton .	.	.	24·5 cwt.	23·0 cwt.	21·5 cwt.
Blast temperature	.	.	.	1100° F.	900° F.	788° F.

One rather striking feature of Dr. Colclough's paper is the omission of any reference to the breakdown of carbon monoxide into CO_2 and deposited carbon in the upper portion of the shaft. It will be recalled that great emphasis was laid upon this reaction, which predominates in the temperature range around 450° C., by Bone and his co-workers, particularly in view of the fact that the deposited carbon is much more active than CO in reducing FeO in the temperature range around 800° C. Obviously, Dr. Colclough has preferred to regard the two reactions as aggregating chemically and thermally to the simple reaction $FeO + CO \rightarrow Fe + CO_2$ in order to keep the issue clear. In doing this, he apparently regards the ability of an iron ore to catalyse CO decomposition as included, along with its willingness to give up oxygen to CO or to carbon, under the term " reducibility." This simplification certainly appeals, but it clashes with some previous concepts. In addition, there does not appear to be any relation between the reducibility of an ore as determined by standard methods and its ability to deposit carbon. For example, Bone, Saunders and Calvert,[2] in comparing a Cumberland hematite with a Spanish rubio ore, found that the former was the better carbon depositor and the latter more responsive to the reducing action of carbon monoxide. The same authors found that Cleveland ironstone was a much more active carbon depositor in the raw than in the calcined state. The point arises as to the relative significance of the two apparently independent properties; how is one to devise a standard test for the determination of the optimum size suggested by the author which will pay due regard to each ?

The author's treatment of the decomposition of carbonates recalls suggestions made by J. E. Johnson and other authorities many years ago, but the fact remains that no one appears to have made out a case for the use of burnt lime in the blast-furnace. Many years ago it was the custom on Tees-side to put the limestone through the Gjers kilns with the Cleveland ironstone, but this practice was abandoned. The physical properties of burnt lime admittedly create a difficulty, but it would be interesting to know the exact reason which led to the discontinuance of the old Cleveland practice.

Referring to Appendices II. and III. of Dr. Colclough's paper, my own feeling is that rather too good a case is made out for ore crushing and grading, and for the full scheme of physical preparation, including sintering. One realises, of course, that, in order to provide contrast, " raw ores as at present " are assumed to be just about as bad as a large mechanical digger can perpetrate. On the other hand, the assumed " ideal " standard of crushing and grading may be better than anyone has yet achieved in practice. One is still left with the conviction that a CO_2/CO ratio of

[1] Alexander, *Blast-Furnace and Steel Plant*, 1944, vol. 32, Mar., p. 346.
[2] *Journal of The Iron and Steel Institute*, 1934, No. I., p. 33.

35 : 65 is rather too optimistic for furnaces carrying a slag weight of 3040 lb. Apparently, Appleby-Frodingham are doing everything advocated by the author in the third case, but the CO_2/CO ratio quoted on p. 230 of Mr. Elliot's Report is 35 : 105 with a slag weight of " up to 27 cwt." (3024 lb.)—this against the ratio of 35 : 65 assumed by Dr. Colclough for approximately the same slag weight. It is only fair to point out, however, that in Fig. 80 of Section VII. of Mr. Elliot's Report the CO_2/CO ratios appear to range from 35 : 72 to 35 : 86—figures not far away from those assumed by Dr. Colclough.

Finally, in assuming a CO_2/CO ratio of 35 : 65 for the physically prepared burdens in Appendices II. and III., is not the author shooting off a gun which should be reserved as an argument for his principal theme— chemical beneficiation ? In the limiting case, i.e., with minimum slag volume, something even better than 35 : 65 would obviously be assumed, but the author would have difficulty in justifying anything better than 35 : 60. American Lake ore practice, with small, readily reducible ores and slag weight around 900 lb., provides a useful pointer, and in this connection Kinney's Illinois furnace [1] showed an average CO_2/CO ratio of 35 : 59 in the exit gases, with the inwall and central gas streams ranging down to about 35 : 130, and the intermediate zones to as high as 35 : 45. The last-named figure refers to gas which, relatively speaking, had ambled leisurely through a concentration of fines, and the velocity standpoint alone would almost certainly place it beyond the bounds of practicability in the top gas as a whole.

Turning to Mr. Elliot's Report, congratulations are due to the author and to his colleagues of the Appleby-Frodingham Works and Central Research Department, Stocksbridge, on the production of so comprehensive and valuable a work. Particularly valuable to the practical operator of blast-furnaces, and almost unique in the literature, is the frank and full exposition of day-to-day problems and of the more serious difficulties which sooner or later confront every furnace manager. General rules are of little value when one is up against a difficult furnace, and in setting down his personal experiences of day-to-day operation and manipulation the author has provided an inestimable work of reference which will be used extensively by the practical man on the job.

In regard to sinter, I confess to membership of the " necessary evil " school and consider my opinions to be supported by the author's Fig. 34. Fundamentally, I regard the function of sinter to be that of enabling ore fines to be included in a scheme of physical preconditioning which has for its object the attainment of that disposition of the descending solid materials which is necessary to ensure correct distribution of the ascending gases over the cross-section of the furnace. Since, from the standpoint of reducibility, the effect of sintering is to degrade material, there would appear to be no object in going beyond the minimum point at which the physical conditions are satisfied. The same conclusion is reached when one looks at the economics of the problem, since the sintering operation perforce tacks at least 4s. 0d. per ton on to the cost of iron-bearing materials. In some practices, of course, other considerations, with the emphasis upon sulphur, come into the picture, but, in the aggregate, the most economic proportion of sinter has to be determined for each furnace plant by operating experience. All this is said in face of the fact that a certain furnace in Great Britain attained its record low coke consumption on practically 100% sinter, but in that case it happened also to coincide with that unit's closest approach to a fully graded burden.

The author mentions (p. 52) that improved reducibility of sinter is to be expected from a decrease in silica content. From this it is not to be

[1] S. P. Kinney, *United States Bureau of Mines*, 1929, *Technical Paper No.* 442.

inferred that low-silica sinters (e.g., those produced from foreign ore fines) can ever reach the point of immunity to damage from surface glazing. Even with some of the richest sinters produced in Britain, the difference between matt and glazed surface can amount to several hundredweights of coke per ton of pig iron.

In the Section on blast-furnace lines, the author's remarks recall that Mr. Fred Clements, nearly twenty years ago, expressed the opinion that bosh tuyeres were a confession of a mistake in furnace lines. I remember also Haven's [1] lament about the way bosh tuyeres "clutter up the bosh," from which I inferred that he did not favour their installation on the new Appleby furnaces. The decision to abandon bosh tuyeres as and when units come off for relining is therefore particularly interesting, since it emanates from the works where, so far as British practice is concerned, bosh tuyeres were first developed to the point of standardisation. Mr. Elliot's remark that bosh tuyeres can be used to boost the driving rate is borne out by Bochum practice during the middle 'twenties.[2] With bosh tuyeres in constant use, this 12 ft. 9-in. dia. hearth furnace maintained the amazing output of 640 tons of basic iron per day, using a burden consisting mainly of North African and Spanish ores and with a consumption of 1760 lb. (15·71 cwt.) of coke. In terms of iron produced per square foot of hearth area per hour, the Bochum figure of 475 lb. contrasts with a range of 89 to 279 and an average of 181·6 lb. for the remaining 21 furnaces included in Clements' survey. In terms of coke burnt per square foot of hearth area per hour, the Bochum figure is 323 lb., as against a range of 110 to 228 and an average of 155·8 lb. for the rest.

The statistical method of examination, applied so extensively in the Section on blast-furnace coke, brings out many interesting points. It is to be hoped that wider use of these methods in our industry will enable blast-furnace operators to give coke suppliers a closer definition of what they require.

With regard to the Section on hearth breakouts, it would appear difficult to justify the considerable extra expense of carbon blocks so far as the North-East Coast is concerned, in view of the good results obtained to date with coke-and-tar ramming. I would be glad if the author would state exactly how much carbon brickwork he has incorporated in the hearth rebuilds of Nos. 9 and 10 furnaces.

I also wish to express disagreement with the practice of bringing a newly blown-in furnace down to low silicon in the course of eight or ten casts. On the North-East Coast we like to see several casts of glazed pig at the outset, and to maintain the silicon content well over 2% for at least two weeks before moving down to authentic steelworks iron. We believe that furnaces handled in this way during the early stages of a campaign are less likely to suffer local or general erosion of the hearth refractories.

In the Section on the utilisation of fuel, it is surprising to find no reference to Clements,[3] who took the question of the desirability of indirect and direct reduction a stage further than Richards, Howland, &c. He showed that in the case of furnaces which, by virtue of low slag weight, high blast temperatures, &c., are generating insufficient carbon monoxide at the tuyeres to reduce all the iron oxides present in the charge, maximum fuel economy is to be obtained by departing from Grüner's ideal by a specified amount, and not, as Richards suggested, by "as far as possible." Clements showed that it was more economical to rectify the deficiency in CO required for reduction by the combination of some of the carbon of the

[1] Blast Furnace and Steel Plant, 1938, vol. 26, June, p. 585; July, p. 694 (see p. 681)·
[2] Clements, "Blast-Furnace Practice," vol. I., schedule 1. London, 1929 : Ernest Benn, Ltd.
[3] Clements, loc. cit., pp. 175–177.

fuel with neat oxygen derived from the oxides of the descending charge (thereby also lessening the deficiency to be made up) rather than by blowing additional oxygen with four times its volume of nitrogen through the tuyeres.   Clements developed this theme still further in his consideration of the hypothetical ideal furnace where maximum fuel economy is attained when 48% of the oxygen removal is accomplished by direct reduction.   Certain it is, however, that under Appleby-Frodingham's conditions, with a slag weight of 3024 lb. and relatively low blast temperatures, Mr. Elliot's conclusion that no benefit would accrue from an increase in the amount of direct reduction is correct.

AUTHORS' REPLIES.

The AUTHORS OF SPECIAL REPORT No. 30 replied : Before dealing in detail with the points raised in discussion, the authors would like to say how grateful they are for the interest which has been taken by so many people. Very many points have been raised in discussion and it is almost impossible to answer every one as fully as the authors would wish; they only hope that other people will add to the practical literature of ironmaking.

Mr. Scott-Maxwell raises several points, not the least important of which is his comment on the lack of progress made by coke research organisations.   The difficulties here are very great, but the need is even greater, and there is no doubt that the future must see much more intensive work towards the improvement of blast-furnace coke.

The first of the two common-sense conditions which the speaker tries to keep before him—" the time of travel of the burden from stockline to tuyeres should be constant from day to day at a minimum value and equal to the maximum time of reduction of the ores being smelted "— appears to epitomise the aim of all blast-furnace work, and the major part of the Report describes some of the many difficulties which lie in the path of full attainment of this object.   Blast-furnace work is difficult mainly because this condition cannot always be maintained.

With regard to the degree of reduction of the ore at the tuyeres, it is thought that the difference between 100% and 60% is a fairly wide variation, and it is believed that all routine furnace operation lies within this range.

Mr. Scott-Maxwell emphasises the need for carrying out investigation, along the lines described by Dr. Colclough, to establish the heat requirements of the ore used.   This is a particularly neglected branch of research.

Everybody engaged in the industry is striving to determine correct furnace lines, and interchange of information can do much to hasten the solution of this problem.

The results quoted by the speaker are extremely interesting.   Is the fact that it was found impossible to make low-silicon iron confirmation of what is said in the Report, that furnace practice is easier and safer with silicon contents of the order of 1·0–1·2% than with lower silicons ?

If all cokes were as low in sulphur as 0·7% furnace operation would be much easier everywhere.   Perhaps, in the future, desulphurisation of coke will attract as much attention as has desulphurisation of iron.

As Report No. 30 was written in war-time, and as the effect of war conditions was ignored as far as possible, furnace outputs and coke consumptions have only been quoted to support particular arguments. There is little point in quoting outputs which have been affected by factors quite outside routine ironworks operation.   The speaker is correct in assuming that the best outputs were obtained in the early days of the plant, as is common to most plants.

The figure for the volume of wind per pound of coke *charged* is normally taken at 50 cu. ft. per min.   It is not agreed that it is difficult to measure accurately the wind volume from a reciprocating blower; the error of such calculation should be less than 3%, which is very comparable with efficient metering.

The impression that Appleby-Frodingham furnaces are blown by pressure is incorrect, as will be seen by reference to p. 173 of the Report. At normal rates of operation the amount of wind blown per square inch of tuyere area varies within wide limits over the ten furnaces, and it is believed that within very wide limits this figure is not important.   During normal operation it varies from approximately 85 to 110 cu. ft. of wind per min. per sq. in. of tuyere area for different furnaces, but it should be realised that when the furnace is working faster than normal the figure quoted automatically increases, and when the furnace is going badly the figure is automatically decreased, which rather confirms that the figure itself is unimportant.

The authors are very grateful indeed for Professor Turner's remarks and fully agree with him that Sir Lowthian Bell's work is still worth reading, and will always be worth reading so long as iron is made in the blast-furnace.

Professor Turner stresses, very rightly, the need of ironmakers in Britain to concern themselves more with reactions when using British ores than with reactions when using rich ores.

The figures quoted by Mr. Patchett as representative of Cleveland work in 1884 overlook the influence of very low throughput rates and of using selected ironstone and beehive coke.   Although the figures, as they stand, are very good, they would not be economic to-day, if only because of the very low output.   It is interesting to learn that the bosh angle in the Cleveland district is of the order of 71–73°.   Mr. Patchett ascribes the freedom from hanging, in spite of this bosh angle, to the good physical condition of Cleveland ironstone.   Surely, to that should be added the effect of good Durham coke.   Mr. Patchett's plea for the proper cleaning of coal is most timely.   Whatever the final cost of the coal, dirty coal represents poor economy.   A rough calculation shows that on to-day's prices an increase of 1% of ash involves an extra cost to the user of this coke of about 1s. 0d. per ton of iron made.

Dr. Stacey Ward, in a very helpful contribution, referred to later in this reply, draws attention to the necessity for exploring methods of agglomeration other than sintering.

The authors are very pleased that Mr. Mather appreciates the fact that, so far as possible, all figures quoted in this Report are long-term figures.   To quote figures representing record performances is liable to do a disservice to the reader.   The comparisons that Mr. Mather draws between to-day's results and those of 60 years ago are in line with what Mr. Patchett has said.   It must be agreed that progress in ironmaking has not been as great as could be desired, and most certainly has not been as great in the metallurgical as in the mechanical aspects.

Dr. Desch and the President stress the need for standardisation of nomenclature and of the method of presenting results in the blast-furnace industry.   It is to be hoped that this point will receive attention by one of the many committees concerning themselves with iron and steel manufacture.

Dr. Saunders' remarks emphasise the complexity of the problems in ironmaking and the need for real research work.   His last sentence epitomises the difficulties in the way, but it is felt that, until work can be done on a full-scale furnace, without fear of the consequences to production and management, the answers will never be obtained.

Mr. O'Connor's thoughtful contribution to the discussion is very useful. The details that he gives of his own practice are extremely interesting, especially that the best work at Corby has been achieved on blast heats of around 400° C.

Fig. A is a valuable extension of the remarks made in the Report about dealing with a hanging furnace. The three conditions indicated in Fig. A are only too familiar to furnace operators, and Mr. O'Connor's description of blowing through hanging, when the hanging is due to packed stock, is very useful.

The elimination of shoddy by an increased magnesia content of the slag is noteworthy and sheds some light on the cause of shoddy. If increased magnesia, with consequent increase in the fluidity of the slag, cuts down the formation of shoddy, it rather looks as if shoddy formation has been associated with a sticky slag. Whether the stickiness of the slag is due to low temperature or to unsuitable composition is obscure.

Mr. Powell's very interesting experience with charging changes on one of his furnaces confirms that each furnace and each set of raw materials constitutes its own problem.

Dr. Rees will be interested to learn that there are now two furnaces with carbon hearths in operation at Appleby-Frodingham. One has been in operation since June, 1944, and to-date is satisfactory. It is, of course, much too early to retail useful experience, but the time has been long enough to enable the operators to form the opinion that the higher thermal conductivity of the carbon brick has not altered normal hearth reactions.

Dr. Rees' remarks regarding fusion-cast refractories draw attention to a type of refractory which has certainly been ignored in the ironmaking industry.

In reply to the point raised by Mr. Dale regarding contact periods in the smaller furnaces, it should be pointed out that in actual fact furnaces Nos. 7 and 8 have a faster rate of throughput than have furnaces Nos. 9 and 6. The remarks made regarding small bell size give the authors a useful line of thought to apply to bucket-filled furnaces.

On the last lining of No. 4 furnace an extra gas offtake was fitted, which has apparently led to very little operating benefit.

Mr. Hollings' remarks regarding coke quality are very much to the point. The authors of Report No. 30 have never come across a coke which was too hard for them. When the Appleby-Frodingham ovens were put into commission a coke cutter was installed on the delivery line to the blast-furnaces. Mr. Hollings will be interested to learn that that coke cutter was removed in a matter of days.

The remarks about the use of carbon as far back as 1902 are interesting and are at least confirmatory that the policy of using carbon for hearth linings is technically sound.

Mr. Hoskison's description of cold-blast practice and its freedom from trouble reads like a description of a blast-furnace manager's paradise. A throughput time of 40–45 hr. should guarantee freedom from most of the troubles associated with blast-furnaces.

Mr. Carruthers describes further constructional precautions which he has taken to offset the threat of hearth breakouts. These precautions, together with the use of carbon bricks, will, it is hoped, go a long way towards removing the threat of breakouts from furnace operation.

The authors agree with Mr. Frost as to the desirability of using the same size of tuyeres all round the furnace, but it has been found impracticable when making large tonnages of very fluid basic iron. He will be interested to know that in the last two or three years breakouts have not been as unknown in America as they were. American technical

journals have now confirmed that two or three furnaces in America have been lined with carbon hearths.

Mr. Scott-Maxwell thinks that there must be something fundamentally wrong in the design of Appleby-Frodingham furnaces, which accounts for irregular stock movement, scaffolds and hearth breakouts. The authors think there is something wrong with the raw materials that these furnaces are having to use.

Mr. Scott-Maxwell appears to believe that all operation at Appleby-Frodingham consists of troubles such as those described in the Report. At all furnaces there have been, and are, long periods of trouble-free operation. If the furnace design, tuyere size, &c., are incorrect, they must also have been incorrect during these long periods of smooth operation, but the materials are far from constant and it is in the materials, the authors believe, that the cause of most of the major troubles lies.

Mr. Hodson's description of bell sizes at Kettering is confirmation that the reasoning of the authors regarding their desired stock distribution is right. Mr. Hodson is to be congratulated on the courage that it must have taken to go to a bell of such small size. It is certainly an important subsidiary point that such a small bell of only 25% of the throat area assists to overcome the problem of throat protection.

Mr. Young very rightly draws attention to the fact that hanging and slipping may be attributable to the coke as well as to the ore. His plea for cleaner coal emphasises the importance of coal quality in successful ironmaking.

The authors are grateful to Mr. Sharp for his correction about the Ormesby furnace. His subsequent remarks serve to emphasise the need for leaving on record unusual furnace experience.

Dr. Saunders' remarks on sinter have been read with great interest. He says that examination of commercial sinters leads to the conclusion that they are made at too high a temperature. That, the authors think, is generally agreed by sinter makers, but the problem is how can one make sinter at a lower temperature when temperature is generated by the combustion of coke? Dr. Saunders points out some of the difficulties in sintering Lincolnshire ores, and goes on to say that "the solution lies in the selection of the raw materials whenever possible." Again, the trouble is that the sinter must be made from the materials available. By and large, the use of works dumps is occasional and not regular. The vast majority of sinter materials are the fines from the run-of-mine ores which come into the plant day by day. Hence, so long as Lincolnshire ores have to be used, then so long will the sintering of these ores present the problems mentioned by Dr. Saunders. This, again, emphasises the need for systematic investigation of all factors involved in making sinter.

Mr. Summers raises the point regarding the desirability of calcining carbonate ores. It is almost certain that calcination affords benefits to a small furnace which outweigh the disadvantages of the high dust production, but it is by no means as certain that this is true of bigger furnaces working at high pressures. Without being dogmatic, the authors consider that calcination is unsuitable for large furnaces.

Dr. Groves emphasises the mineralogical difficulties in the way of concentrating low-grade home ores and gives a lot of very useful information. Again, Dr. Groves underlines the necessity for further work to be done on a national basis. With that view the authors are in complete agreement. Dr. Groves rightly stresses the financial limits to expenditure on ore dressing. It is difficult to lay down a definite limit to the amount which can be spent to enrich the ore, but, by and large, the finished concentrate, in a condition for charging to the furnaces, should

not cost more per unit of iron than an imported ore of similar iron content.

The authors incline to agreement with the somewhat pessimistic view expressed in Dr. Groves' last sentence.

Dr. Groves' suggestion that the industry should not hesitate to consult the Geological Survey has been noted with thanks. The authors believe there are several problems which could rightly be referred to that body for help and guidance.

Mr. Towndrow's contribution to the discussion is extremely useful; it is pleasing to the authors that their example in admitting to trouble has been followed by Mr. Towndrow. In a way, his remarks are not a contribution to the discussion so much as a useful addendum to the Report, and the authors prefer to think of them in that manner.

Perhaps the most interesting point brought out by Mr. Fowler is the essential need with some British ores to have a high slag volume in order to deal with the very large amount of sulphur in the ores and coke. His broad classification of blast-furnace practice in the British Isles is new and is undoubtedly correct.

In reply to Mr. Campbell's remarks, the authors do not know the details of his particular system, but presume he is referring to a method of electrostatic separation. They are in agreement that it should be considered, but they understand that one objection to such systems is that the material should be bone-dry.

Dr. Taylor underlines what was said by his colleagues of the Geological Survey on the need of the industry using iron ores to consult the geologists. The aim of the geological investigation outlined in Dr. Taylor's last sentence is undoubtedly sound and will be of great value to the steel industry.

In reply to Mr. Garson, running the furnace down and charging coke only was tried to remove the scaffold in No. 6 furnace without success. It should be emphasised that this scaffold was much more permanent than most and, because of its size and nature, resisted normal methods of attack.

The authors are extremely chary of expressing an opinion whether the bottom trouble referred to in his last paragraph was due to the high percentage of manganese. Much more information would be necessary before anyone could express an opinion.

In reply to Mr. Walker, the authors are far from satisfied with their methods of sampling in connection with the bedding plant. A very great deal of work is being done and will be the subject of a future publication.

The authors would utter a word of warning. They would hesitate to say that an increase in output to an extent of 210 tons per week plus a reduction of 1·4 cwt. of coke was solely due to the removal of part of the moisture from the Northampton ironstone. As with all blast-furnace results, it is seldom possible to draw clear-cut conclusions like this on the basis of a short period of work. The authors are very strongly of opinion that savings do result from the drying of Northampton ironstone, but are sorry that they conveyed the impression that the saving was as great or as definite as shown above. Work has been done with more complete drying of Northampton ironstone, but the results indicate that little benefit is obtained if the moisture is reduced much below 8%. This may be due to the fact that the greater part of the burden (Frodingham ironstone) contains more than this amount of moisture. Whether the whole of the burden should be dried or semi-dried opens up a very interesting field for investigation.

In regard to the points raised by Dr. Taylor in connection with Section IX., it is pointed out that, although the gas analyses quoted from

Special Report No. 18 [1] show lower CO_2 contents than those of Schlesinger (used for this survey), the analysis of the solids at 900° C. shows that reduction is scarcely 80% complete. Therefore, the remainder of the reduction must be carried out at temperatures where the tendency is for reduction to become " direct." Obviously, any CO_2 initially formed would not be apparent in the gas analysis. What appears to be an exaggerated preoccupation with the 700° isotherm is the desire to ensure that the greatest possible reduction is carried out in a region of the furnace where the gaseous product of the reaction is stable, thus reducing the tendency towards loss of carbon by solution and uneconomical reduction in the hearth.

Concerning the effect of moisture in the burden the authors agree with Dr. Taylor that carbon is not necessary for the dissociation of moisture, but carbon is always there in the closest possible contact with the moisture and with the catalyst.

Dr. Stacey Ward deplores the fact that the blast-furnace has for too long been the Cinderella of iron- and steel-works plants. The authors hope that the Cinderella will find a Fairy Godmother in the new British Iron and Steel Research Association.

His remarks regarding the behaviour of the North-East Coast furnace confirm the views expressed in the Report.

In reply to Mr. Patchett, the authors note that he does not agree with the theory that oxygen penetration is the cause of hearth breakouts. Mr. Patchett will be interested to learn that the cooling system of the South furnaces circulates more water than would the system which he describes. As a matter of interest, the amount of water circulated round the hearth cooling staves of No. 9 or No. 10 furnace is approximately 1300 gal. per min.

The authors note Mr. Hacking's comments regarding sinter. The viewpoint one adopts towards sinter is necessarily governed by plant conditions. There is no doubt that the argument used for sintering, say, Mesabi ores does not necessarily apply to British ores. At the same time, the use of sinter has, in the aggregate, reduced the cost of pig iron. When the percentage of sinter in the burden rises above a critical value (which will be different for different plants and materials) furnace operation becomes more difficult.

The authors agree with Mr. Hacking's remarks regarding bosh tuyeres and the application of statistical methods in the industry.

In furnaces Nos. 9 and 10 approximately 140 tons of carbon brickwork have been installed in each furnace. This was for a hearth diameter of 22 ft.

The authors are aware of good results obtained in some places from coke-and-tar ramming, but they are also aware of most unsatisfactory results obtained from this procedure in Great Britain. It was because of the lack of control in coke-and-tar ramming that the authors decided to use pre-formed carbon. If the use of pre-formed carbon secures greater immunity from breakouts then the extra expense is more than justified.

Mr. Hacking expresses his preferment for slow blowing-in. The authors suggest that this is a matter for each operator to decide after trying both methods. It should be pointed out that the best records of furnace life have been obtained on furnaces blown-in fast.

The authors note Mr. Hacking's agreement in his final comments that

[1] Blast-Furnace Reactions Research Committee, " Reports upon Blast-Furnace Field Tests. I.—An Investigation of a Blast-Furnace Smelting Principally Lincolnshire Ores at the Frodingham Works of the Appleby-Frodingham Steel Co., Ltd.," *The Iron and Steel Institute*, 1937, *Special Report No.* **18**.

no benefits would accrue at Appleby-Frodingham from an increase in the amount of direct reduction.

Dr. J. H. CHESTERS also replied to the discussion on Refractories : I should like to reply to a few of the points raised. I agree with Colonel Stein that it is most improper to speak simply of " percentage porosity." It should always be described as either " apparent " or " true." In all our work, however, where a porosity is quoted, followed by a bulk density and an apparent specific gravity, the porosity is " apparent." Indeed, it is very rarely that we even calculate the true porosity.

Our tests on the slag resistance of 70% alumina bricks have been very limited, and, following Colonel Stein's remark, we will carry out further work to see whether his contention that this type of product has a much higher resistance to blast-furnace slag than ordinary high-alumina bricks is correct. Meanwhile, it may be of interest to him to know that we are installing a ring of such bricks in the tap-hole of a furnace just going into operation.

We are grateful to Dr. Marshall for his valuable contribution. The first indications that good results might be obtained with what he refers to as South Yorkshire bricks came from him, and the preliminary results, both in laboratory tests and in works trials, confirmed the experience reported from Park Gate.

Coming to the remarks made by Dr. Rees, I am afraid that there is one general trend which is almost inevitable when one is trying to get something done and to push ahead in any field, and that is that in one's enthusiasm to develop the new theory one forgets what people have done before. I can assure him that such forgetfulness does not represent our real feeling. I have said several times that it is only people who have big and progressive research departments who can hope to make use of the work that other people in the field are doing, and I venture to suggest that there are few who have made more use of the work done by the British Refractories Research Association and other pioneers than ourselves. I mean " use " in the sense that we stand on the shoulders of those who have worked before.

We do appreciate what has been done on blast-furnace refractories and on brick-making practice. We have shown an example of what can be done—a stove which looks new after $4\frac{1}{2}$ years. We claim no credit for it, except that we used it carefully ; we neither designed it nor had anything to do with the specification of the refractories. It is probably true to say that in Britain more work has been done on refractories during the war than in any other country in the world. Our progress, of course, is partly due to the fact that we have been forced to accept, and therefore study, materials which we would not have chosen. I think that the work of the British Refractories Research Association, for instance, on chrome ore, has been absolutely first-class.

I would like to refer to the question of carbon deposition. I did not refer to it in my opening remarks, because the bulk of the data given (in the part of the Report dealing with the lifting of the superstructure) was communicated by another company, who very generously shared it with us. I did not feel it was wise to discuss it, but we do feel that it is both vital and interesting. We have had at least two furnaces recently where the shell has burst at the top owing to carbon deposition. In one case the whole superstructure rose a matter of 10 in., carrying with it the bell and ancillary gear. When we opened those furnaces out we found that the trouble was carbon deposition. I agree with Mr. Green, however, that we cannot, unfortunately, assess the probability of that happening in terms of the test on the original brick. Even if the brick has

a completely clean character and shows no tendency to deposit carbon, it may pick up iron—for example, ferrous chloride, as we have shown in another Section of the Report, which might hydrolyse during a shut-down and give iron oxide ; this might then act as a catalyst for carbon deposition.

At the end of the Report there is a statement that we have built into the blast-furnace four indicators at the top of the stack which show what is happening, and it is stated that the top of the stack has moved up more than would be expected merely by thermal expansion of the brick-work. I think I am right in saying that that movement has been con-tinuous, though slower, ever since this Report was written. It has now reached 9 in. on one side, as compared with the 2 or 3 in. which would be the theoretical movement due to thermal expansion. We still, therefore, have that problem to face.

We are sorry if the rather expanded data on the cold crushing strength, given with reference to the weathering of firebricks, has created the impression that we place particular stress on this property. It happens to be a convenient way of measuring the deterioration in storage, but we would assure Mr. Green that, provided that bricks have sufficient strength to stand up to the abrasion in the furnace, we are not particularly con-cerned with crushing strength as such. The expansion is in the stack of the furnace, where we hope, ultimately, to be able to dispense completely with armouring by the use of bricks of sufficiently high abrasion resist-ance. This property should ideally be tested directly, but it has been shown by a number of workers that, generally speaking, abrasion and cold crushing strength go hand in hand.

With regard to Mr. Girling's point about stoves, because we are throw-ing out two rather challenging ideas—one, that a very high-alumina brick, well-fired, is good, and the other, that the siliceous bloating brick may be better—we do not want to condemn all other bricks. We feel that if a brick is well-fired it might do its job in a stove even though it had a medium alumina content. To our surprise, however, we find that in certain conditions the siliceous brick also does a very good job. My own preference would be for a brick of the 40–42% alumina type which was really volume-stable, rather than for one of the bloating type. To get over shrinkage by causing expansion is hardly an engineering procedure.

Mr. Girling has correctly interpreted our rather vague sentence about zoning in checkers. We are not convinced of the value of zoning, par-ticularly if it has to be achieved by the use of a relatively complex checker shape.

Mr. W. W. STEVENSON also replied : Dr. Stacey Ward has usefully elaborated on the recoking tests given in Section IV. of the Report and confirms our view that a reasonable content of volatile matter is desirable in blast-furnace coke. Regarding the high content of carbon monoxide obtained from the 1250° C. and 1550° C. recoking experiments, there is little doubt that reduction by carbon of the oxide constituents of the coke ash has occurred. Such reactions are used commonly in the vacuum-fusion method for the determination of oxygen in iron and steel, and it can be stated, for example, that ferrous oxide is reduced completely by carbon *in vacuo* at about 1100° C., manganous oxide at 1150° C., silica at 1350° C. and alumina at 1570° C. Dr. Ward will realise, of course, that our main objective in these recoking tests was to obtain information relative to hydrogen, for the purpose of the added hydrogen reducibility tests, with which to compare the direct tests using synthetic blast-furnace gas.

We thank Dr. Saunders for his comments on sinter and regret that, although we have had an opportunity of studying his modified porosity method, it has not yet been tried out at Stocksbridge. We are unable to correlate Dr. Saunders' two statements (a) that most commercial sinters are made at too high a temperature, and (b) that an excess of coke in the sinter mix would result in improved sinter by the trapping of carbon in the final product. Under no *commercial* conditions of sinter production can we possibly imagine admixed coke escaping reaction during the sintering operation. In our experience increased coke invariably means increased temperature, with consequent increased fluxing and lower reducibility. Incidentally, we have not found preferential slag formation in Appleby-Frodingham practice, and this is shown in Table XIX. (p. 51) of the Report. We consider the capability of sinter to withstand crushing in the furnace to be of secondary importance, as compared with the desirability of the sinter being sufficiently strong to withstand handling between the sinter plant and the furnace bell.

The excellent contribution of Dr. Groves, regarding our mineral resources, does not call for specific reply; we can only agree with the useful comments contained therein.

Mr. Walker comments on our coke tests, and we are glad to note that, like Dr. Ward, he agrees with our view that a higher-volatile coke will have greater reactivity from a reduction point of view at temperatures above 1000° C. We are definitely in accord with Mr. Walker's statement that the fixed carbon of coke does not represent the full story of the reduction process in the blast-furnace. We are fully familiar with the excellent properties of Durham coke, and Mr. Walker's data on 1·9% volatile-matter coke from this source are very illuminating.

Regarding Dr. Taylor's suggestion that greater care should be taken in the preparation of the armouring bars before inserting them in the furnace, we would agree immediately that calorising should prove very effective from the viewpoint both of corrosion prevention and also of heat resistance. This is a suggestion well worthy of trial. As regards protecting the bars by pickling or phosphating followed by a coat of priming paint, to tide over the interval between placing the bars and blowing-in, we feel that this would be merely delaying the commencement of carbon deposition, as we know of no paint which would withstand the temperature after blowing-in, and we reassert that metallic iron is a sufficiently powerful catalyst for the carbon deposition reaction, irrespective of the behaviour of oxides of iron in this connection.

Mr. E. A. GOODLAND replied to comments on Section IV.: In reply to Mr. Johnson's concluding remark, I would say that the full sentence, of which he has quoted half, does not enjoin blast-furnace operators to perform the obvious, but states that a more constant coke quality would enable blast-furnacemen to adopt the most suitable measures for making the best of the coke. As Mr. Johnson doubtless knows, under present conditions blast-furnace operators are compelled to adopt measures tending to poorer economy, because they have to overcome difficulties due to poor coke which are more pressing than difficulties due to poor economy.

With regard to Mr. Scott-Maxwell's first remarks, I feel that the reason why coke research organisations have not achieved more in finding a suitable coke index is that there has not been sufficient co-operation between them and plant operators in the application of possibly valuable suggestions made by the research people to full-scale practice. Concerning his remarks about the occurrence of petrographic separation, we have investigated this, but have not yet found any evidence for it at Appleby-

Frodingham. We suspect, but are not yet in a position to prove, that size segregation (in which petrographic separation may be involved) is responsible for patches of weak coke. The separation of $+ \frac{1}{4}$-in. coal and its return to the crusher for further crushing is a development that we should much like to see tried. We have done it in box tests without any success at all so far.

The interlocking of the belt tripper with the wagon tippler should do much to help correct blending, as only too often the best intentions are nullified by their improper application in routine work.

With regard to Dr. Stacey Ward's valuable remarks, I am pleased to say that one aspect of the influence of cell structure on bulk density and, more broadly, on the behaviour of the coke in the furnace has been receiving initial investigation, namely, the heat of wetting of the coke. First results were favourable, but they need checking and then confirming by routine observations over a period before the heat of wetting can be claimed as a useful index.

It is usually possible in these statistical investigations to choose one set of figures which gives more favourable results than another. The time which an ordinary coke-oven staff can devote to such problems is not usually sufficient to correlate all possible pairs of parameters, and it was in the hope that someone with more time and ability in statistical matters would be able to wring out a better story that we included so many rather dull Tables of figures.

There is little doubt that the figures for the quantities of gases in the coke lead to much speculation concerning the origin of the oxygen. Nevertheless, however it arrived, it appears to be there and therefore will enter the blast-furnace reactions, and it is from that point of view that we have looked at it.

Mr. Riggs appears, from his remark, to have overlooked the fact that the coals used for coking are not quite the same to-day as they were sixty years ago. A specification related more closely to what is practicable at present would be of more value to a coke-oven manager coking a blend of South Yorkshire coals.

With Dr. Desch's plea that there should be more uniformity in the basis to which figures should be calculated we are in full agreement. The British Standards Institution have tackled the matter with regard to the testing of coke-ovens (B.S.S. 999–1942) and other forms of carbonising plant. A test code for blast-furnaces on the same lines could, no doubt, be drawn up, and adherence to the methods laid down therein would go a long way towards solving this problem.

Dr. T. P. COLCLOUGH replied to comments on his own paper : It is very gratifying to find that my paper aroused so much interest, and thanks are due to the many Members who took part in the discussion for their valuable contributions. The outstanding features of the discussion are the recognition of the importance of the coke consumption in the general economy of pig-iron manufacture under present conditions, and the general acceptance of the central theme of the paper, that for efficient operation it is essential to prepare adequately the raw materials consumed before they are charged into the furnace. This, together with the experience demonstrating the advantages of the large blast-furnace as compared with the relatively small unit of the last-war period, represents probably the most marked advance during the last ten years in blast-furnace thought. It is to be hoped that these principles will be fully applied in the approaching period of reconstruction.

While, in general, the proposals made in the paper meet with approval, some Members raised objections to the use of the waste-gas analysis as a

criterion of efficiency in the use of coke. It is readily admitted that this basis is not suitable for the comparison of practice data under all conditions. It is recognised that with the use of silicate or highly magnetic ores of an irreducible type, in which reduction can be effected only at temperatures in excess of 1000° C., or with very lean ores, which generate an excessive slag volume, the theoretical CO/CO_2 equilibrium is, in practice, unattainable. On the other hand, with the easily reducible ores of the Midlands, to which attention was specially directed, and with the soft hematites of the United States of America, a very large proportion of the reduction can be accomplished in the stack of the furnace at temperatures below 800° C., resulting in increased use of the CO generated in the hearth and approaching closely to the theoretical CO/CO_2 ratio, provided that the suitable physical conditions are established. These desired conditions were fully described by more than one Member taking part in the discussion. The CO/CO_2 ratio of $1·87/1·0$ suggested in the paper as standard, compared with the theoretical of $1·5/1·0$, is purely arbitrary and is put forward as a standard capable of attainment in practice under conditions which must vary from day to day. That this suggested standard can be reached has been fully demonstrated over a period of years in Great Britain and is verified by recent investigations in America.

It is to be noted that no attempt is made in the paper to postulate coke consumption or to compare performance data on any existing practice. The coke consumption to be aimed at can be estimated from a consideration of the thermal requirements of the particular burden, and the accuracy of such estimates has been demonstrated by experience.

The data contributed by Mr. Carruthers on the application of blast-furnace gas to other heat-consuming units in a composite plant will be of definite interest to Members and especially to those engaged in the engineering side of the industry. They may, however, be interpreted as indicating the large proportion of the potential heat of the coke charged into the furnace which in present practice is not used in the furnace itself but carried away in the waste gas. Thanks are due to Mr. Carruthers for setting out so clearly the magnitude of this loss to the furnace operation. It is of importance that it should be recognised that, when the furnaces are operated on a more efficient basis, the loss of heat, sensible and potential, will be smaller and that other heat users, such as boilers, will have to be supplied with additional fuel to make good the deficiency, and that both existing and new plant must be designed on a basis adequate to take care of the changing conditions.

IRONMAKING AT THE APPLEBY-FROD-INGHAM WORKS OF THE UNITED STEEL COMPANIES, LIMITED.[1]

By G. D. ELLIOT AND THE STAFFS OF THE APPLEBY-FRODINGHAM IRONWORKS, SCUNTHORPE, AND OF THE CENTRAL RESEARCH DEPARTMENT, STOCKSBRIDGE (THE UNITED STEEL COMPANIES, LTD.).

This Report, published as Special Report No. 30, is divided into the following eleven Sections :

A summary of the subject-matter of these Sections will be found on pp. 141 A–143 A of the present volume.

At the Autumn Meeting of the Institute in 1944 the Report was discussed jointly with a paper on " Considerations on Blast-Furnace Practice " by T. P. Colclough (this Journal, pp. 359 P–374 P); the discussion is recorded under the title " Discussion on Blast-Furnace Operation and Problems," on pp. 375 P–452 P of this volume.

Later the Report was presented and discussed at a Joint Meeting of the Institute and the Lincolnshire Iron and Steel Institute, held in Scunthorpe Technical School, Cole Street, Scunthorpe, on the 23rd and 24th January, 1945, at 7.30 P.M. each evening; Mr. J. N Kilby, President of the Lincolnshire Iron and Steel Institute, was in the Chair. The discussion which then took place is recorded below.

DISCUSSION.

First Evening.

Mr. ELLIOT briefly presented the Report.

Mr. J. N. KILBY (Chairman) : The paper emphasizes the importance of collaboration in compiling such a monumental study, and indicates the important part slag volume will play in the future. Any effort to reduce slag volume, whether in the blast-furnace or the steel furnace, paves the way for lower fuel consumption throughout and, ultimately, bigger steel outputs.

I have often been told one cannot see inside a blast furnace, but I believe it to be like all metallurgical processes and to possess indicators in the form of slag and iron quality which become the eyes to the reactions fulfilled.

It was refreshing to hear that sometimes poor iron is made and shoddy is experienced. I have related over some years coke and pig-iron quality to results in the melting shop and rolling mill through to sales yield, and

they all prove that there is a connection between iron quality, costs, and yield. It is futile saving 2s. 6d. at the blast-furnace and putting 15s. on the product.

Wing-Commander J. B. R. BROOKE (Messrs. John Lysaght, Ltd.) : Mr. Elliot rightly points out that however much sinter is used in the burden the slag volume is not reduced; the volatile matter and moisture are merely driven from the burden. With old-fashioned furnaces I think we all came to the conclusion that to work with an iron yield of less than 30% in this district gave rise to a disproportionate increase in coke consumption. Mr. Elliot is talking about furnaces which are operating on a quite different basis, and I was interested to hear him say that without a reduction in slag volume coke consumption cannot be greatly reduced. He is referring primarily, I assume, to pre-war practice. I should like to ask him whether, with pre-war or present practice, excluding last year, he feels that the addition of a certain amount of foreign siliceous ore would be an advantage. I think this an important question in view of the way in which we are controlled now, being either allowed or not allowed, as the case may be, to use the materials we would like to use.

The other point which I think is of paramount importance is whether as good a quality of iron is made with a large furnace as with a smaller one. Mr. Elliot states that it is possible to work with a very much lower slag basicity, and I can well appreciate that. In the first place, owing to the volume of the furnace, there is such a reserve of heat that a higher available hearth heat results, which enables the melting point of the slag to be reduced, and this in turn gives more available heat. I should like to ask if the staff of Appleby-Frodingham Works are equally satisfied with the iron now produced as they were with the iron from the more basic slag, because with the old-fashioned furnaces we do agree that we must have iron produced under a hot, limey slag.

Mr. ELLIOT, in reply : If we were allowed to use foreign ores we should be very happy. I think that is an extremely important point for the future. Before this war, with coke at its 1938 price, we could not afford to use foreign ore, but I am not at all sure that with coke at the price it is now and the price it is likely to be after the war, we shall be unable to afford not to use foreign ore. Economic factors must always determine whether or not we use enrichers of that nature. From a technical point of view the use of foreign ore is desirable very largely because it reduces the slag volume.

With regard to the second point about iron quality, I think I am right in saying that, if we leave out the unfortunate year 1944, the steel industry preferred iron from the bigger furnaces for the following reasons : (1) It was more regular in analysis, and (2) it was undoubtedly hotter.

Mr. G. R. WALSHAW (Appleby-Frodingham Steel Co., Ltd.) : One thing Mr. Elliot did not mention in giving the lines of No. 4 furnace was the new distribution system on the top of the furnace, having a revolving bell, which was installed about 1908. I have no knowledge of any other works putting on one of these new tops until this one was in operation. I never saw the actual result of this top, but I believe that work was much better after its installation than before. I think that might have been referred to in the history of the Frodingham plant.

There used to be a great deal said, years ago, about dry blast on furnaces. It was Gayley, I think, who froze the blast and took all the moisture out of it before it entered the furnace. Is dry blast considered worth while on a furnace plant to-day ?

Mr. ELLIOT, in reply : I should have mentioned No. 4's distributor because it was the first mechanical distributor designed for a furnace. It antedates the McKee top. The furnace was blown in in 1905 and the top put on in 1907 and is working to-day.

Dry blast has been used in this country at Wishaw Ironworks, but its use was discontinued after some time. It was used in U.S.A. in the early years of the century by Gayley, and the results were quite sensational. Dry blast went out of favour because it entailed the use of dangerous, expensive, and awkward apparatus. In the last 5 or 6 years the drying of blast has been introduced into the Southern States, and there is undoubtedly a strong case there for it. One plant in the Northern States is actually wetting the blast to a constant figure. So far as our own practice is concerned, we have to clear up all our problems of irregular burden, moisture, and coke quality before we consider drying blast.

Mr. J. A. NAISMITH (Messrs. John Lysaght, Ltd.) : Mr. Elliot referred to the fact that sinter made from local ironstone was weak. To overcome this weakness, they added siliceous Northampton fines, thereby forming silicates which strengthened the structure of the sinter.

At one period last year there was a serious shortage of siliceous stone, and in order to maintain sinter production, we added sand in its place. This sand did not give the desired results. We found that sand alone could not combine with the limey stone to form silicates (it remained as quartzite in the final product), unless some liquid medium was first formed. The sand could then dissolve in this and form silicates. Did Mr. Elliot encounter similar difficulties during this period ?

The second query is about suction in sintering. Over a period we took several samples with different suctions and we found that when the suction was increased it resulted in slagging and severe channelling in the sinter bed. The slagging made the sinter patchy and very friable; when broken it crumbled, revealing unburnt coke and calcined stone. Analysis of the waste gases proved very little action to be taking place. We came to the conclusion that, as suction is increased beyond a set limit, the quality of the sinter deteriorates.

Mr. Elliot also mentioned that Northampton stone behaves much better in the furnace after drying, owing to dehydration of the clay in it, which renders it non-sticky. This stone contains alumina, present in the form of a clay, which, when dried, bakes hard. With handling, however, does this not yield a high percentage of fines and dust ? Could this clay not be washed off ? By this means, as well as by getting a non-sticky feed of ore, one could maintain the alumina in the slag at, say, about 18% instead of permitting it to rise. Would this be beneficial, especially in large furnaces ? Everyone appreciates the difficulties that would be encountered with a sticky slag of high alumina content.

How does sulphur vary with basicity ? Are the same desulphurizing properties obtained as with a slag of very high basicity ?

Mr. ELLIOT, in reply : When we introduced Northampton fines into a sinter mixture we got a stronger sinter because the increased iron gives a stronger iron bond and the increased silica gives a stronger silicate bond. We found that sand in sinter was only satisfactory if the free quartz went into solution, and we found that it would not go into solution unless there were already Northampton fines there.

The point about suction is extremely interesting. From the reverse point of view, on the Greenawalt plant, we have made modifications which reduced the suction and we think that quality was thereby improved.

I am a bit of a heretic about alumina. The best work of the South

furnaces has been done with alumina contents of 20%; we can go to 22% without getting into serious trouble. With regard to the point about washing the ore to remove that alumina, if we had a method of washing it away we should remove some of the iron with it. In connection with concentration methods, the ores have such a low initial cost that one cannot afford to spend a lot of money on concentration.

The sulphur in the iron from 22-ft. furnaces is as low as the sulphur in iron made with high-basicity slags in smaller furnaces. I am speaking of normal times; throughout this Report we have tried to keep out war conditions. Under normal conditions, with normal burdens, we can regularly produce sulphur contents under 0·075% with silicon well under 1% from the 22-ft. furnaces, with a slag basicity of 1·17 lime/silica ratio. If we go lower than that and come down to 1·10, we can do so for a short time only; if we get down to 1·05 we are soon off grade.

Wing-Commander BROOKE : I do not know whether the melting points of the lower-basicity slags of the big furnace are comparable with the melting points of the slags of the acid-burden process. Are we approaching the acid practice here or are we still dealing with practice at Frodingham ?

Mr. ELLIOT, in reply : These slags were still more of a normal Frodingham nature than of the glassy acid type.

Mr. W. W. STEVENSON (Central Research Department, The United Steel Companies, Ltd.) : Perhaps Mr. Elliot would like me to enlarge somewhat on the recent necessity at Appleby-Frodingham of using sand for balancing the burden. A few months ago Mr. Elliot's supplies of Northampton ore were reduced by half, and he had to begin using sand in one furnace in order to make up for the deficiency in silica. After briefly considering flue-dust losses, he and I planned a series of experiments on sand admixture to the sinter. The results of these experiments showed that in the complete absence of Northampton ore in the sinter mixture, a suitable sinter could not be produced from local stone and sand; in other words, raw silica, with its melting point of over 1700° C., does not flux successfully with the lime and iron oxide of Frodingham ironstone. On the other hand, the presence of only a small amount of Northampton ore in the sinter mixture permitted the sand to be taken " into solution." The inference we drew was that the sand required the presence of a silicate into which it could fuse, thereby enriching the silica content of the lime–iron–olivine, which we know is the basis of the sinter bond in Lincolnshire practice.

Dr. J. H. CHESTERS (Central Research Department, The United Steel Companies, Ltd.) : The system of bedding ores at Appleby-Frodingham is so obviously a success that it might well be applied by other industries faced with the problem of variable raw materials, e.g., the silica-brick trade is faced with the problem of quartzite of variable analysis. I have talked to silica-brick makers about the possibility of bedding, and their reply is always: " Yes, but what about the cost ? " Surely the iron-maker cannot afford to pay a high cost. It would be very interesting to hear from Mr. Elliot approximately how much it costs to bed iron ore in the way it is done at Appleby-Frodingham.

Mr. ELLIOT, in reply : Obviously the operating cost will be dependent on the size of the installation, but it should be possible to put down a plant to deal with 20,000 tons a week at less than 6d. per ton. This should cover the process out of the wagon and out of the bed. It is not expensive because, for one reason, the labour charge is extremely low.

Mr. A. C. WATKISS (Messrs. Richard Thomas & Baldwins, Ltd. (Redbourn Works)) : *Section III., Furnace Plant Design.*—Would Mr. Elliot give his experience and opinion on a plate-cooled bosh compared with a spray-cooled bosh. Our experience at Redbourn on the larger-type furnace leads us definitely to prefer a plate-cooled bosh. The next point is throat armour; we have found 5 rows of mild-steel bars, 4 ft. 6 in. long by 8 in. wide and $\frac{3}{4}$ in. thick, bent at right angles and fixed into the stockline brickwork, very successful on all of our furnaces. When No. 4 furnace was blown out recently after an output of over 900,000 tons and a throughput of over 5,000,000 tons, the top armour was in remarkably good condition.

Regarding furnace lines, we have travelled a rough road from the old-type furnaces with high flat boshes, to the more modern furnace with larger hearth and lower bosh. There is one outstanding change that has given us much smoother operation, and that is the use of the lower bosh. In my opinion the height of the bosh is more important than bosh angle provided the angle is approximately 77° or over. The maximum height of bosh should be no more than 12 ft. 6 in. from the centre line of the tuyeres or about 11 ft. above the top of the hearth.

Section IV., Coke.—We have had considerable furnace trouble with poor-quality coke and are now running three tests on samples from the belt (shatter, Cochrane and Micum) and also the bulk-density test from weighed charging buckets. We find quite a good correlation between furnace performance and the shatter test. We like a coke giving, after the shatter test, 78–81% on a $1\frac{1}{2}$-in. screen, also a low percentage of fines, not exceeding 3%, below $\frac{1}{2}$ in. Coke giving over 82% on the $1\frac{1}{2}$-in. screen is much denser and reduces the driving rate. The Micum test gives a useful figure, but we cannot correlate it with the shatter test. The bulk-density test is the most satisfactory one. It is affected by size of coke and moisture content, however, and we have to take this into consideration.

Section VII., Operation.—Mr. Elliot favours blowing-in fast. We have that experience and find it an excellent method. Our No. 1 furnace was blown in at 5.45 A.M. on April 10, 1944. The first cast was tapped at 11.20 P.M. on April 11. The iron gave on analysis : 8·39% silicon, 0·019% sulphur, and 1·16% manganese, using a procedure very similar to that given in the Report. We did not get on to basic-iron quality as fast as Mr. Elliot mentions ; we took 5 days. Results were excellent in every way.

Mr. Elliot mentions in this Section that there is no positive correlation between furnace performance and tuyere size. We find the relation more marked. We have tried tuyere sizes from 5 in. to 7 in. in dia. and have even used 8-in. dia. tuyeres. If we reduce the size of tuyeres, we find the furnace becomes sluggish, the rate of driving decreases and the output of iron falls considerably. Although the desired velocity is in the region of 110 cu.ft./min./sq.in. of tuyere area, we have had good operation when this figure was in the region of 95 cu. ft. without any excessive scouring of brickwork around the tuyere zone. I should like Mr. Elliot's opinion on this question of volume and tuyere sizes.

Blast Temperature.—I agree that one cannot carry high blast temperatures and get smooth operation. Our range is 850–950° F. with normal operation. Mr. Elliot states that with limey slags they can carry higher blast heats. We find the opposite, but have to carry temperatures high enough to keep the tuyeres clean.

Burdens.—With regard to the iron content of the burden, Mr. Elliot mentions a minimum of 28%. Unfortunately we have not been near that figure. We have done very good work on 26–27%. As to enrichment of the burden with foreign ore and/or scrap, we find that it affects the iron cost if we exceed 10%.

Slag Composition.—I note that Mr. Elliot makes no comment on the difficult range of slags. We have to make low-silicon basic iron in this district and we find that our slags are very viscous, with an alumina content of about 19%, which gives us trouble in supplying sound slag for road-making. Honeycomb slag is very prevalent. I have operated with slags having an alumina content of 15–17%, and there is a marked difference between a slag containing 17% of alumina or under and one containing 19–20%. It is probably a question of temperature ; Appleby-Frodingham work hotter furnaces.

Hanging.—I should like to confirm Mr. Elliot's opinion on this trouble, because it is a very controversial subject with operators. We cannot blow through hanging ; we have tried all ways for many years. There is only one exception, *viz.* when hanging is due to a " hot " furnace ; then the use of cold blast is successful.

Shoddy Iron.—We have had experience of shoddy and we find it more prevalent when working on a cold siliceous slag. An increase in the lime and coke does clear shoddy in a certain time. One thing Mr. Elliot did not mention—they may not be familiar with it at Appleby-Frodingham— is dead iron. This iron will not work in the melting shop. I have found no explanation for it, and it is usually made on a siliceous slag with a normal-working furnace, the silicon content being, say, 0·9–1·5%. It has a very close fracture and the total carbon is low—1·8–2·3%. This iron runs like lead and the temperature is usually slightly lower than our normal temperature of iron.

Distribution.—I quite agree with Mr. Elliot that distribution is the most important thing. On our small furnaces we find that ore on the bell first and then coke gives the best results. If we put coke on first and then ore, we get a freer furnace, but coke consumption is higher. On the larger furnaces we have tried all methods, although bucket charging is not very flexible. Our experience is that small charges give a higher flue-dust loss. The two methods of charging that give the best results are " Redbourn charging " (coke on bell, then ore dump, coke dump, ore dump, repeat) and " double charging " (coke on bell, then ore dump, ore dump, coke dump, repeat). The former gives slightly higher flue-dust loss, but a smoother-working furnace ; the latter gives a slightly lower coke consumption. We are now running on " Redbourn charging " from 6 A.M. to 10 P.M. and on " double charging " from 10 P.M. to 6 A.M.

I should like to mention the effect of weather. We find that wet weather has a serious effect on our operation, resulting in poorer burden, bad distribution, &c. Our practice, of course, is more primitive than that of the Appleby-Frodingham plant. We crush local ironstone only to approximately 6 in. Our burden is usually up by 4 cwt. and coke by 2 cwt. in winter.

Fireclay Mixture for Tap-Holes.—Does Mr. Elliot find that the high percentage of grog in the mixture they use causes excessive wear on the worms in the clay gun owing to abrasion ? We have had to reduce our percentage of grog by 10% and are getting good results at the tap-hole and much less trouble with gun worms.

Mr. ELLIOT, in reply : I was interested to hear of Mr. Watkiss's preference for a plate-cooled bosh. At Appleby-Frodingham we have only two of our furnace boshes cooled in this way, and during nearly six years' work on these two furnaces we have not had to change a single plate cooler. When these furnaces were off for hearth repairs in 1944, it was found that the bosh lines were almost as new. The principal drawback to sprayed boshes is undoubtedly the amount of attention required to ensure that the bosh is receiving an adequate amount of water at all

times; sprays have the habit of choking and thus causing the bosh to be unequally cooled.

The throat armour in these two furnaces, inspected at the stoppages mentioned above, showed scarcely a trace of wear. The furnaces had, at the time, made about 750,000 tons each.

With regard to desirable bosh dimensions, I fully agree that the height is more important than the bosh angle, for the reasons given on pp. 81 and 82 of the Report.

The 35% of grog used in our clay mix does not seem to give any undue wear of the gun worms. These are changed every 3 months and built up by welding. A 3 months' life does not give sufficient wear to make the welding a big job.

Mr. Watkiss's remarks regarding tuyere area do not agree with experience at Appleby-Frodingham. At our ten furnaces we have a very large range of values for the air blown per square inch of tuyere area. Two of our most successful furnaces, No. 7 and No. 9, have values of 85 and 110 cu.ft./sq.in./min., respectively, when doing their best work. I would refer Mr. Watkiss to the comments on p. 174 of the Report.

Mr. Watkiss drew attention to the effect of alumina on slag viscosity. During the unfortunate period last year when a shortage of Northampton stone necessitated the use of large quantities of sand in the burden, the alumina in our slags was below 15% and the effect of this increased the fluidity of the slag, even that with high lime content, to a marked extent.

Dead iron is not a very frequent occurrence at Appleby-Frodingham, but quite a lot of attention is being paid to the question of the causes underlying its production. Iron of normal analysis but of subnormal temperature is often described as dead iron. The formation of shoddy is very often an accompaniment of this mysterious trouble.

Second Evening.

Dr. CHESTERS briefly reviewed the contents of Section V. of the Report, with particular reference to the development and application of carbon bricks.

Mr. I. M. D. HALLIDAY (Central Research Department, The United Steel Companies, Ltd.) : I do not propose to go through the sections on refractories in the Report in detail, but merely to indicate the more important highlights—the things which we in The Central Research Department are most interested in at present.

Blast-Furnace Refractories.

(1) *Variability of Properties.*—With any property measured in the laboratory we tend to get a series or range of results which characterize the material under investigation. This not only applies to fireclay but to carbon as well. With fireclay, however, the condition is very much worse. Whereas the typical crushing strength may be 2200 lb./sq.in. for the best high-alumina brick, the bricks that have a crushing strength of 2200 lb./sq.in. are perhaps only those occurring with the maximum frequency in any given wagon of bricks; there are also many much better and many much worse. With carbon brick, the average strength of which is about 6000 lb./sq.in., the frequency peak tends to be higher and the control much better. The chance of a consignment of carbon bricks having a crushing strength close to the average, say, 6000 lb./sq.in., is very much greater than if for 37% alumina bricks an average crushing strength were specified of 3200 lb./sq.in. and for 40% alumina bricks 2200 lb./sq.in.

The same applies to porosity, permeability, and various other pro-perties. This factor of variability should be remembered when the blast-furnace lining is considered.

(2) *Use of High- and Low-Alumina Bricks.*—The use of high- and low-alumina refractories in blast-furnaces has been standard practice at Appleby-Frodingham. It is a relatively old idea, but has not yet been accepted by everybody. It is better to have in the hearth higher refractoriness, and in the stack greater strength and hardness of brick.

(3) *Tap-Hole Clays.*—In the section on tap-hole clays, two things seem rather important. First, if we take a raw clay and measure the permanent changes in size when it is fired to progressively higher temperatures, as shown in Fig. 65, we find it contracts, then expands, and finally shrinks. For any given clay we get a different curve, but in most clays we get the expanding or bloating effect. The only value of that property, previously, seemed to be in its application to steel ladles. The bloating effect is very marked in ladle brick and that expansion is utilized to make these ladles self-sealing to the action of steel. In tap-hole clays we also make use of this property.

The tap-hole clay mixture used at South Works is composed of 45% of fireclay, 35% of grog, and 20% of coal. As the temperature rises, the characteristic curve for the clay shows that it bloats between 1000° and 1200° C. As shown in Fig. 68, the heat of the furnace fires the clay in the tap-hole and shrinkage occurs at the hot face. There is a bloating effect at the lower-temperature zone, the expansion of which causes a tightness, and this keeps the tap-hole closed.

The other important point is that the green tap-hole clay is plugged in with 20% of coal. The coal is added to the batch to help fire the whole of the plug. We have found that the coal in the tap-hole does burn away. But how does the coal burn away ? It must have oxygen to burn, and therefore must get it from somewhere. One theory is that most of the oxygen comes from the outside through the pores of the clay. The point, however, is that conditions in the tap-hole and in the middle of the brickwork lining are found to be oxidizing. This is important in connection with the theory of breakouts.

Stove Refractories.

(1) *The Design of Stoves.*—The design of the refractory checker should be not only robust but simple; fancy shapes are not necessary. In the design of the stove itself, the checkers should be quite free of the stove walls and able to move vertically under the changing temperature con-ditions. Quite a generous horizontal expansion joint should be left right round between the lining of the chamber and the contents inside. Com-bustion chambers built elliptically or by means of a cross wall show weak-ness. The better design of chamber is the simple, circular chimney, and, like the checkers, it should be quite free to move.

(2) *Deterioration in Service.*—What happens to refractories during their life in the stove ? Stoves can be run in two ways—on clean gas or on semi-clean gas—and that introduces two different problems. In stoves run on unclean gas the trouble is attack by dust from the gases. The attack on the refractories is worst in the chamber where the temperature is a maximum, but it is also serious in the top 2 or 3 ft. of checkers. The dust causes a slagging action (*see* Fig. 73), the attack being due to iron oxide, lime, and smaller percentages of the alkali oxides.

In clean gas, the iron oxide and lime contents of the gas are removed, but it has been found that the alkali oxides have been somewhat con-centrated. Other troubles then arise owing to vitrification and spalling of the checkers and of the brickwork. Alkali pick-up of the bricks may

be up to 8%—almost all K_2O. This appears to cause shrinkage and vitrification of the working face of the bricks and results in the observed spalling by producing stress concentrations at the interface of the vitrified surface and non-vitrified brick behind it. A very interesting fact is that bricks which have a bloating tendency on refiring appear to be almost free from this trouble.

(3) *Rigidity-Modulus Work.*—If a $9 \times 1 \times 1$-in. bar is cut from a brick, twisted between two chucks, and the amount of twist which occurs under an increasing torque measured, we can calculate the modulus of rigidity. We have done this for different brands of bricks, as received and also after refiring to 1200°, 1300°, and 1400° C. The results obtained are shown in Fig. 75, and it can be seen that all the brands except one show, in general, an increase in the rigidity modulus with increase in the firing temperature. The exception is the brand of bricks which has a tendency to bloat. It seems that this difference in rigidity can be related to the fact that these bricks also do not cause trouble in service due to spalling. This investigation is still continuing.

Hearth Breakouts.

Fig. 88 shows the cut observed in the hearth brickwork when No. 9 furnace at South Works broke out, and also the zones in the brickwork next to the site of the breakout. We were able to obtain a few samples of these zones and found the working face of the brick was metal-impregnated and badly slagged at the outer edge or layer. By analysis the outstanding characteristic of this metal-impregnated face, which was $1\frac{1}{8}$ in. thick, was found to be the very high FeO content (14%) at the outer circle of this zone—the limit of metal penetration. Examination of the hearth brickwork of a furnace subsequently blown out (No. 6 furnace, North Works), confirmed the existence of this FeO zone. FeO contents as high as 17% were obtained, and the zone could be several inches in thickness. The slagging action of such percentages of FeO is able to bring the melting point of the refractory down below 1300° C. and even down to 1260° C. Thus the working face of the brickwork is cut off bodily, and in positions of maximum wear repeated cutting in this manner leads to a breakout.

The crux of the problem is, where did the oxygen come from to form such quantities of FeO ? There must be a chimney effect in the hearth brickwork, sucking the air and moisture through the pores, as indicated in Fig. 94. The CO/CO_2 ratio of the gases in the pores may then be sufficiently low to oxidize the iron in the pores and produce the FeO zone.

To stop this happening a hearth would need to be sealed off right across the bottom by metal sheets so that no air could get in. A better idea would be to build the hearth in carbon brick as well. Carbon bricks are not worn by metal nor attacked by FeO or slag. No penetration of iron into the pores would occur and the carbon brick could not burn if the hearth were sealed off as indicated.

Carbon Deposition in the Stack.

Trouble has been experienced as a result of the lifting of the super-structure, due to expansion of the stack brickwork. It has long been known that the reaction $2CO = CO_2 + C$ can take place and deposit carbon as soot and graphite in the brickwork. This reaction was found in the laboratory to take place to the greatest extent at about 450° C., and certain substances, mainly iron, promote its occurrence by acting as catalysts. In testing, the iron in the brick results from particles of iron oxide in it, which have become reduced to the metal. So the reaction

takes place in the laboratory, if carbon monoxide is passed through the pores of the brick, at a temperature of about 450° C.

Further, when the reaction does occur there is an expansion in the brick, due to the formation of deposited carbon. For that reason we might try to get bricks with the iron oxide taken up in the brick texture, say as relatively inactive silicate, and so obviate the chance of this happening. But the important thing is that if we build a stack, no matter what the quality of the brickwork is, the furnace gases can travel up through the pores of the brickwork and emerge at the top of the stack wall near the furnace casing. In doing that they carry in all the dirt found in crude blast-furnace gases. Even if iron oxide as such is not present in the brick originally we get dust, with a lot of iron oxide, carried into the pores and the carbon deposition reaction can proceed. When this happens, if armouring bars had not been set in the wall, the inface at a few feet below the stockline, where the temperature ranges between, say, 400° and 600° C., would be disintegrated, and get knocked out. The protection thus afforded by the armouring bars is linked with their normal rôle of protecting the throat against impact of the burden.

We studied a furnace with armouring bars of the type shown in Fig. 97, and found by examination of the structure of the armouring bar that we could plot a straight line through the estimated temperature at different positions. We could also measure the position where we got the maximum deposition (about 6 or 7 in. thick) of carbon. The corresponding temperature range for deposition of carbon was found to be 400°–600° C., as had been observed in the laboratory.

From temperature gradients the temperature range of maximum deposition of carbon, 400°–600° C., is seen to lie in a band from the working face at the throat inwall—at a level, say, a few feet below the stockline—to near the furnace casing at a level some 10 ft. above the lintel plate. Therefore, deposition of carbon will tend to occur in this vertically slanting band of temperatures within the stack wall right round the furnace, and will result in a conically shaped zone of dis-integrated brickwork. The unaffected brickwork to the inside of this cone is for the most part keyed against itself so far as movement towards the centre of the furnace is concerned. So when deposition of carbon takes place the brickwork on the outside and above the zone of deposition is forced up to accommodate the resultant expansion. Normal expansion allowances at the top of the stack wall therefore become insufficient, and the wall lifts the charging bell, hopper, and the rest of the superstructure. Measuring devices have been set on top of the brickwork of the stack of No. 6 furnace, North Works, and the increase in height of the whole stack can be measured from day to day during its life. No doubt Mr. Elliot can supply the latest figures of the rise which has taken place to date.

Mr. ELLIOT, in reply : I have some figures of growth and No. 6 furnace has already grown between $7\frac{5}{8}$ and $9\frac{1}{4}$ in. When it grows to $10\frac{1}{2}$ in. the engineers will come along for three days, or three weeks, to take the top off and make more room. The furnace was blown in in August, 1943.

Mr. C. A. J. BEHRENDT (Appleby-Frodingham Steel Co., Ltd.) : With regard to hearth brickwork, are we satisfied that the iron oxide found in brick taken from the hearth existed as iron oxide before the furnace was blown out ? Is it not probable that it was injected into the brick as metallic iron in a very finely divided form, and remained as metallic iron until the blowing-out and cooling process was more or less complete, and that the oxidation then took place in contact with air or moisture ?

Mr. HALLIDAY, in reply : If the brickwork is examined, it can be seen that the FeO has slagged the refractory to a liquid. The glassy slag zone left is an iron-oxide–alumina–silica slag. The facts that the temperature since the furnace went out of commission has always been lower than the maximum temperature, and that the slagging action takes place behind the working face, do not allow any other explanation. We can only say that it occurred when the hearth was actually working.

Mr. A. BRIDGE (Appleby-Frodingham Steel Co., Ltd.): I am not as yet convinced that carbon deposition is the cause of the lifting of a blast-furnace superstructure, because, during thirty years' experience with blast-furnaces, it was not until 1940 that I encountered, or even heard of, an occurrence of this nature. It is also important to note that, if carbon deposition is the cause, only two of the ten furnaces under review have been affected.

I am aware that in one or two isolated cases similar troubles have occurred elsewhere in this country, and I think I am correct in stating that here again the trouble was first experienced during 1940.

Mr. HALLIDAY, in reply : One reason is that comparatively recently the design of the throat armouring has been slightly changed. One kind of armouring bar which came into favour was designed with short lengths bent downwards at the inwall and next to the casing, as shown in Fig. 97. That type of armouring bar tends to hold the front and back of the stack wall together, and if expansion occurs owing to carbon deposition it must act upwards. It would have been much better to have designed the bar without the down-turned lip next to the casing. Quite a lot of work has been done on different types of armouring. Some furnaces have a cage hung from the top of the wall, or from the hopper, and quite free of this brickwork. Such armouring may result in throats with less tendency to rise.

The other reason is that perhaps the gas analyses are slightly different. There is probably more carbon monoxide in the furnace gases under present-day working conditions.

Mr. BRIDGE : I do not agree that the shorter throat-armour bar has any connection with the trouble, because identical bars have been fitted in other furnaces with no ill-effects.

Mr. ELLIOT, in reply : As Mr. Bridge points out, we have ten furnaces and so far only two have lifted. Serious lifting has occurred in many other plants. I know of one plant with four blast-furnaces, all relined in two years, which lifted so badly that they ripped the shell plates. This is another blast-furnace problem which has not received sufficient publicity. We are aware of cases of lining growth leading to disruption of the steel casing many years before 1940. Johnson [1] mentions swelling of the throat lining prior to 1917.

It may be of interest to record that when No. 5 furnace was blown out for relining in 1945, extensive carbon deposition was found to have taken place around the armouring bars. The amount of deposition had been great enough to lift the superincumbent brickwork bodily, without disruption of the bricks. Carbon to a depth of several inches was found between the bar and the disturbed brickwork.

In recent years we have, at Appleby-Frodingham, adopted dipped joints. There is no allowance for undue growth, and I think that is one reason why we are getting that expansion. Expansion takes place in all

[1] " Principles, Operation and Products of the Blast-Furnace," p. 259.

furnaces, but it takes place in less degree on those furnaces working with a very low CO content in the gas and where the armouring bars are short. The two furnaces most prone to growth are two giving trouble on account of a high CO content in the gas. If we built furnaces again with wide joints in the stack, we should not have trouble. Personally, I think the policy of building with tight joints is absolutely right at the bottom, but whether it is right at the top remains to be seen.

Mr. A. JACKSON (Appleby-Frodingham Steel Co., Ltd.) : Some years ago we tried graphite bricks in mixer-type iron ladles without very great success. After they had been in use some time they were found to wear very unevenly, and this was subsequently said to be due to manufacturing troubles, owing to which the lamination was not always in the same direction in every brick.

I understand that the bricks mentioned in the Report are rather different from the old graphite bricks, but we did try some of the bricks such as were put into the blast-furnaces in a small iron ladle. After about 10 casts the bricks had burned away to such an extent that we took the ladle off and discontinued the trial. We are considering other trials in a totally enclosed iron ladle, but I should like Dr. Chesters to confirm or deny whether these bricks burn away more rapidly than the older type of graphite brick.

Mr. Halliday said that he sealed the bottom of the furnace to keep out the air. I should like to know how that was done. I can visualize considerable expansion and contraction when the furnace is working, and the method used may be of help in sealing the regenerator chambers in steel furnaces.

In another part of the Report the point is made that the bigger the furnace the less basic the slag, and I wondered if, instead of making the slag less basic, it were kept equally basic, would the sulphur be lower in the iron produced ?

On p. 181 Mr. Elliot states : " To make a low-silicon iron with highly basic slags is a process too expensive to be contemplated." This is a point not likely to be as easily disposed of as this. There is a steadily increasing demand for steels with very low sulphur content, say, below 0·025%, and to obtain this much lower-sulphur pig will be necessary than that shown in the Report. This low-sulphur material can be obtained with low-sulphur iron, say, down to 0·03%, and 0·05% can be considered the maximum in normal open-hearth practice and will necessitate slag volumes of probably up to 30%. There is no doubt that this will very considerably reduce the efficiency of the open-hearth furnace. Furthermore, there is little doubt that this low sulphur content is necessary for certain types of steel. What method of operation does the author propose to meet this demand ?

Mr. ELLIOT, in reply : With regard to the quality of iron obtained from lean slags, the Table on p. 176 quotes the average slag analyses for six months' work in 1940; Table A gives the iron analyses during that period. I have no hesitation whatsoever in saying that furnaces Nos. 9 and 10 will show lower silicon and sulphur and a greater regularity than any of the other furnaces. In addition, at the present time furnaces Nos. 9 and 10, instead of working on a lime/silica ratio of 1·18, are working on 1·3. The iron is higher in silicon and higher in sulphur. Throughout this Report we have tried to exclude war factors, and where results are affected by war conditions we have left them out. We have collected figures that we can reproduce under more normal conditions.

The method of sealing the bottom of a furnace which has been adopted

consists in laying a steel-sheet floor over the full area circumscribed by the hearth jacket at about 3 ft. below the level of the hearth bottom. These sheets are laid loosely with wide lapped joints. This was done in the hope that any expansion changes would be taken up by the sheets sliding rather than by their buckling, as would possibly be the case if the sheets were welded together.

TABLE A.—*Iron Analyses at Appleby-Frodingham Furnaces (6-Months' Period).*

Furnace No. .	3	2	7	1	4	5	6	9	10
Hearth dia., ft. .	11	11	14	15	17	17	17	22	22
CaO/SiO_2 ratio .	1·42	1·40	1·37	1·34	1·30	1·31	1·30	1·18	1·18
Silicon, % . .	1·04	0·91	0·98	0·77	0·65	0·73	0·96	0·81	0·86
Sulphur, % . .	0·082	0·070	0·088	0·076	0·063	0·075	0·087	0·074	0·068

We are criticized for the statement made on p. 181 : "To make a low-silicon iron with highly basic slags is a process too expensive to be contemplated." Furnaces Nos. 9 and 10—I am speaking about what we consider normal conditions—should each average over 3000 tons a week of good basic iron with a lime/silica ratio of 1·17. If we made, as we could, an iron containing 0·5% of silicon and 0·04% of sulphur, we should make out of these same furnaces about 1000 tons each per week and the coke consumption, instead of being in the neighbourhood of 21 cwt., would be 30 cwt. I submit that is too expensive for us to contemplate, especially as the price of coke is going up. In the future, unless we can find new methods and reduce coke consumption, no matter what iron we get, the melting-shop and steel plants will go out of business. The future will demand that coke consumption is the first and foremost consideration in any integrated iron and steel plant, and it may well be that the steel plants will have to modify their practice to use iron of a quality which enables us to get down to an even lower coke consumption. With coke, as it is to-day, at 56s. per ton, you have not to use much before you have spent a few shillings on the pig iron. I feel strongly about this. It binds up the whole question, as the Chairman has stressed. Cheap steel is made, not in the steel furnaces and not in the blast-furnaces, but in the coal mines and ironstone quarries. We must face the fact that in this district we are going to get more and more sulphur delivered in our raw material. At this time we are using normally about 45,000 tons of ironstone out of this district per week. Less than 10,000 tons of it is brown oxidized stone, with a sulphur content of over 0·14%; but inside 7 years every ounce of stone we lift will contain over 0·3% of sulphur.

In addition, the Northampton stone has the same tendency. All Northampton stone has now a sulphur content lower than 0·1%; but every ounce of it we use in five years' time will have 0·5%. We have seen sulphur contents going up during the war; actually, sulphur contents are a war-time factor. The collieries are not digging clean coal, &c. The coking coals in this country are increasing in sulphur. Instead of the average blast-furnace burden running, as it has been in this district, about 0·14% sulphur with 1·1% sulphur in the coke, it is going to reach 0·5% in the burden and $1\frac{1}{4}$–$1\frac{1}{2}$% in the coke. The more lime we use the more slag we make. The more slag we make the more coke we use. Every hundredweight of slag demands one-third of a hundredweight of coke. You heard the Chairman stress the quality of pig iron. He told us we were a lot better at making slag than iron. If we are going to stop

making slag we shall have to give the melting shop poorer iron. I believe phosphorus helps to make slag. We cannot get it down. Sulphur also makes slag.

There are two possible ways out; one is by improving the ironstone. By improving I include mixing enriching agents, purer foreign ores, whereby we shall concentrate the burden by admixture. We have also to consider concentration of the ores; inevitably this is expensive. Alternatively, we have to make what iron we can, as cheap as we can, at a lower cost and introduce an intermediate stage before the steel furnace. This is a personal opinion. In the future we have to think of desiliconizing and dephosphorizing the iron before it goes to the steel furnace.

Mr. KILBY (Chairman) : Mr. Elliot has indicated that the blast-furnace must give us something better for the steel plant. I entirely agree with him, and this change may well mean the road to cheaper and better steel outputs.

In 1917, at Sheffield University, I gave a paper on " Basic Open-Hearth Steel Production," and in it I stated that we must concentrate on making an ingot and not a saleable slag. I believe you will agree with this to-day, and that it was sound argument even as long ago as 1917, although at that time people disagreed with me.

The steel furnace is not the place for cleaning up the shortcomings of poor coke and of subsequent bad working or poor-quality materials in stages up to the mixer in the steel-melting shop. A steel furnace is a most expensive apparatus in which to eliminate impurities or to manufacture slag. Our so-called mixers call for the utmost attention, being generally ineffective and of very low capacity.

I believe the processes through which the iron goes before entering the steel furnace should be planned so as to impose a maximum quantity of slag of 10% on the steel-furnace operations. This calls for primary furnaces, not mixers, capable of adequately feeding the steel furnaces and absorbing all bought miscellaneous scrap, while leaving the works mill scrap for direct charging. Further, the time periods and load should be really systematized and controlled, and the variables levelled out in the primary furnace. The primary furnace, to do this, would have to be equipped to develop the necessary heat to do the work.

There is no obstacle to our greatly augmenting the outputs of steel furnaces operating on hot metal if we change the present methods of feeding the furnaces.

Again, as far back as 1917, I stated : " The load of a basic furnace, other things being equal, is in ratio to the total amount of silica the slag is to carry." This holds good to-day more than ever before; that is, whilst the position of basic refractories is so weak.

Mr. E. D. HARRY (Appleby-Frodingham Steel Co., Ltd.) : I have been rather interested in the Section on fuel utilization, and reading it just brings out again the complexity of the blast-furnace. In this Section the reactions of direct and indirect reduction have been clearly brought out. In the case of direct reduction, which is reduction taking place above 700° C., the CO_2 formed by reduction of the FeO by CO reacts with carbon to form CO. The author, along with other writers on the subject, states that this CO_2 will react with coke carbon, and by so doing will rob the furnace hearth of coke. In the zone of temperatures between 600° and 400° C., carbon monoxide will dissociate $(2CO \rightarrow CO_2 + C)$ and the ore particles will be impregnated with this deposited carbon. I wonder whether it is likely that the CO_2 formed by reduction of FeO by CO in the zone above 700° C. will react with this deposited carbon in preference

to the coke carbon. In support of this view, I should mention that the deposited carbon is present in a very much more chemically active form than the coke. Also, it is present in the pores and interstices of the ore particles, and so is in a most favourable position to react with the CO_2 as soon as it is formed and before it gets into contact with coke. If this is true to any extent, it means that direct reduction does not rob the furnace hearth of coke, since the carbon dissolved is deposited carbon formed from CO.

On p. 229 it is stated that quite a large proportion of the hydrogen found in blast-furnace gas must come from moisture in the burden, Carbon will not react with steam below 400° C., and it would appear to me that by the time the burden has reached a temperature zone of 600° C., there will be very little moisture left. Is it not likely that the combined water in the burden is mainly responsible for the hydrogen (apart from hydrogen derived from moisture in the blast) in the blast-furnace gas?

Mr. J. A. BOND (Appleby-Frodingham Steel Co., Ltd.): Calculations on furnace practice show that approximately 17% (equal to about 450 lb.) of carbon fails to reach the tuyeres. What has happened to this carbon? It has been oxidized, either by CO_2 or iron oxides. Oxidation of deposited carbon by iron oxide can proceed very rapidly at 750° C., and it must be remembered that the downward movement of the solids in the furnace is comparatively slow and that it may take an hour for the temperature of the solids to rise from 700° to 800° C. But, while oxidation by FeO is possible and rapid in this temperature zone, the speed of the reaction $CO_2 + C = 2CO$ is practically nil, being extremely rapid at 1000° C., slowing down to about 800° C., and remaining round about equilibrium until a temperature of 600° C. is reached; then the reverse reaction $2CO = CO_2 + C$ commences and gains velocity with falling temperature down to 400° C.

It thus appears that, for possibly an hour at temperatures between 700° and 800° C., conditions are favourable for the reaction FeO + C (deposited) = Fe + CO, but most unfavourable for the reaction $CO_2 + C = 2CO$, and it seems likely that the deposited carbon has been oxidized before it can reach the zone in which it can be dissolved by CO_2.

If, however, deposited carbon is dissolved as Mr. Harry suggests, the product is CO and the reaction is endothermic. We require to convert a maximum amount of carbon to CO_2 and pass it out of the furnace as such, and the greater the amount of reduction taking place below 700° C. the less CO_2 will be produced at temperatures high enough to take part in the endothermic reaction $CO_2 + C = 2CO$.

Regarding the second question, as to whether it could not be the combined water and not the ore moisture which produces the hydrogen in the furnace gases, I should say that with ores of normal moisture content, water from both sources takes part in the reaction. The furnace burden contains 8 or 9% of combined water in any season of the year, but the weight of hydrogen in the furnace gases per ton of iron produced is reduced by the drying of stone (which has no effect on the combined water) and increased by heavy rain. This rise in hydrogen content is somewhat masked by the increased gas make which is the usual result of charging wet materials. It is, therefore, probably true to say that, normally, moisture and/or combined water produce the unaccounted-for hydrogen, but that excessive moisture in the ores charged leads to an abnormal loss of carbon to the furnace.

Mr. STEVENSON: I should like to make three points. First, on the question of carbon deposition on the armouring bars about which

Mr. Bridge, as ironworks engineer, is so worried. The reaction responsible—the dissociation of 2CO catalysed by iron (or iron oxide) to give $CO_2 + C$—is a reversible reaction, and I would suggest that the answer to this reversible reaction is to introduce carbon into the zone of reaction ; thus, if the armouring bars were placed in position with carbon bricks around them, the tendency for carbon deposition would be considerably reduced, as the reaction is unlikely to proceed from left to right on account of the presence of massive carbon immediately alongside the armouring bars. I would therefore suggest to Mr. Elliot that he tries fixing his armouring bars in with carbon bricks in order to minimize the deposition and consequent lifting of the superstructure.

Secondly, very little has been said to-night about coke, but I would like to draw special attention to the recoking tests carried out at Stocksbridge, the results of which are reported on p. 104. These tests on the recoking of coke at temperatures up to 1500° C. showed greatly increased contents of hydrogen evolved from the coke of highest volatile matter (1·59%). After the finding of this additional hydrogen in the high-volatile coke, reducibility tests were carried out on standard materials, and these showed increased rates of reduction in the presence of more hydrogen than is normally present in the top gas of the blast-furnace. I may say that these laboratory results have been borne out in actual furnace practice.

My final point deals with pp. 200 *et seq.* of the Report on the method of charging. This particular part of the Report covers approximately two pages, omitting the diagrams, and to my mind the subject-matter could, with advantage, be increased considerably. I regard this phase of the subject as the main direction in which we are going to have immediate improvement in blast-furnace practice in the future. Greater attention must be paid to sizing ; definite sizes of materials should be fed to the furnace at definite intervals, and this, of course, means greater screening and stocking facilities. For example, instead of charging a nominal 4-in., if a true 4-in. or a true 2-in. were fed at definite times to obtain horizontal segregation of size in the furnace, I am sure that a substantial reduction in coke consumption would follow automatically.

OBITUARY.

Dr. THOMAS SWINDEN died suddenly on October 27, 1944, while at the Stocksbridge works of Messrs. Samuel Fox and Co., Ltd., at the age of fifty-nine ; he had recently resumed his duties after an absence from work of several months due to illness. Born in Sheffield on August 15, 1886, he was educated at Sheffield Central Secondary School and at Firth College, Sheffield (later University College, Sheffield, now Sheffield University), where he studied metallurgy under the late Professor J. O. Arnold, F.R.S., and obtained an Associateship in Metallurgy in 1905. He was awarded an 1851 Exhibition Scholarship which he used to study at the Universities of Uppsala and Stockholm under Dr. Carl Benedicks and to gain practical experience in a number of Swedish ironworks. On returning to England he re-entered Sheffield University and obtained the degrees of Batchelor of Metallurgy in 1907 and Master of Metallurgy in 1909, eventually receiving the Doctorate in 1913. As a result of his valuable and fundamental researches on tungsten and molybdenum steels he was, in 1909, awarded an Andrew Carnegie Research Fund Scholarship of The Iron and Steel Institute. This was renewed for a further period of two years in 1911, and in 1913 he was presented with the Andrew Carnegie Gold Medal. After some experience with Dr. P. Longmuir as a consulting metallurgist, he joined the firm of Messrs. Samuel Fox and Co., Ltd., as Chief Chemist in 1909. Later he became Chief Metallurgist, then Works Manager and, finally, Managing Director. In 1932 he was appointed Director of Research of The United Steel Companies, Ltd., while retaining his seat on the Board of Messrs. Samuel Fox and Co., Ltd. He was also a Director of the Distington Hematite Iron Co., Ltd., and the British Magnesite Corporation, Ltd.

Dr. Swinden was noted for the wideness of his interests in metallurgical problems. These ranged from researches on alloy steels to investigations in the fields of pyrometry, open-hearth practice, the quality of coke, and the properties of refractories. Evidence of this diversity of interest is to be found in the numerous papers he wrote for technical societies connected with the steel industry. The following papers were published by The Iron and Steel Institute :

" Carbon-Tungsten Steels " (*Journal*, 1907, No. I.).
" The Bristol Recording Pyrometer " (with P. Longmuir, *Journal*, 1909, No. I.).
" The Constitution of Carbon-Tungsten Steels " (*Journal*, 1909, No. II.).
" Carbon-Tungsten Steels " (*Carnegie Scholarship Memoirs*, 1911).
" A Study of the Constitution of Carbon-Molybdenum Steels " (*Carnegie Scholarship Memoirs*, 1913).
" Some Notes on Cold-Rolled Strip Steel " (with G. R. Bolsover, *Journal*, 1927, No. I.).
" Chromium-Steel Rails " (with P. H. Johnson, *Journal*, 1928, No. I.).
" Controlled Grain Size in Steels. The Effects on Mechanical Properties and Some Suggestions Concerning the Theory Involved " (with G. R. Bolsover, *Journal*, 1936, No. II.).
" An Examination of the Oxygen Content of a Basic Bessemer Rimming Steel " (with W. W. Stevenson, *Journal*, 1940, No. II.).
" The Fractional Vacuum-Fusion Method for the Separation of Oxides and Gases in Steel. Further Practice and Typical Results " (with W. W. Stevenson and G. E. Speight, *Journal*, 1941, No. I.).
" Dolomite Bricks for Use in Steelworks " (with J. H. Chesters, *Journal*, 1941, No. II.).

Reports and Papers of the Committee on the Heterogeneity of Steel Ingots.

" A Note on the Determination of Nitrogen and Some Results " (with W. W. Steven-
   son, Sixth Report, 1935, Section VI.).
" Some Experiments on Gases in Iron and Steel and their Effect on the Solidification
   of Ingots " (with W. W. Stevenson, Sixth Report, 1935, Section VIII.).
" Rimming Steel.—A Study of Composition Variation from Outside to Centre "
   (Seventh Report, 1937, Section II.).
" Some Further Experiments on Gases in Iron and Steel and their Effect on the
   Solidification of Ingots " (with W. W. Stevenson, Seventh Report, 1937, Sec-
   tion V.).
" The Fractional Vacuum-Fusion Method for the Separation of Oxides and Gases
   in Steel " (with W. W. Stevenson and G. E. Speight, Eighth Report, 1939,
   Section VI., Part 2B).
" Rimming Steel.—Further Examples of Composition Variation from Outside to
   Centre " (Ninth Report, 1939, Section III.).
" The Manufacture of Rimming Steel at Workington by the Acid Bessemer Pro-
   cess " (with F. B. Cawley, Ninth Report, 1939, Section IV., Part 1).
" Rimming Steel.—Additional Studies of the Composition Variation from Outside
   to Centre " (*Journal*, 1942, No. II.).
" A Note on Diffusion in Rimming Steel on Soaking at about 1300° C." (with
   W. W. Stevenson, *Journal*, 1942, No. II.).
" Rimming Steel.—An Examination of the Carbon and Oxygen Relationship in the
   Solidification of a Basic Open-Hearth Steel " (with W. W. Stevenson and G. E.
   Speight, *Journal*, 1944, No. I.).
" An Examination of a Rimming-Steel Ingot Containing 0·29% of Carbon " (*Journal*,
   1944, No. I.).
" Rimming Steel.—Experiments on Melts of Rimming Steel Composition in the
   Laboratory High-Frequency Furnace " (with W. W. Stevenson and G. E.
   Speight, *Journal*, 1944, No. I.).

Reports of the Oxygen Sub-Committee.

" The Fractional Vacuum-Fusion Method for the Separation of Oxygen and Gases
   in Steel. Further Practice and Typical Results " (with W. W. Stevenson and
   G. E. Speight, Third Report, Section II., Part *B*, *Journal*, 1941, No. I.).
" An Examination of the Oxygen Content of a Basic Bessemer Rimming Steel "
   (with W. W. Stevenson, Third Report, Section IX., Part *A*, *Journal*, 1941, No. I.).
" The Fractional Vacuum-Fusion Method for the Separation of Oxides and Gases in
   Steel " (with W. W. Stevenson and G. E. Speight, Fourth Report, Section II.,
   Part *A*(*b*), *Journal*, 1943, No. II.).
" Determination of Nitrogen " (Fourth Report, Section II., Part *C*, *Journal*, 1943,
   No. II.).
" The Examination of a Series of Alloy Steels " (Fourth Report, Section III. (*h*),
   Journal, 1943, No. II.).
" The Determination of Oxygen and Hydrogen in Liquid Steel " (Fourth Report,
   Section IV., *Journal*, 1943, No. II.).

Report and Paper of the Corrosion Committee.

" A Note on the Relative Efficiency of Restrainers in the Pickling of Carbon Steels "
   (with W. W. Stevenson, Fourth Report, 1936, Section *E* (4)).
" Relative Atmospheric Corrodibility of Ferrous Metals " (with W. W. Stevenson,
   Journal, 1940, No. II.).

Paper of the Steel Castings Research Committee.

" Leaded Manganese-Molybdenum Steel " (*Journal*, 1943, No. II.).

In addition he was responsible for numerous unsigned sections of
Committee Reports.

The positions of importance held by Dr. Swinden in the iron and steel
and associated industries were numerous. He was Vice-President of the
Refractories Section of the British Ceramic Society, a Vice-President of
the British Cast Iron Research Association, Chairman of the Technical
Committee of the Alloy Steels Association, Chairman of the Committee
on the Weldability of Ferrous Metals of the Institute of Welding,

Chairman of the Open-Hearth Refractories Joint Panel of the British Refractories Research Association and The Iron and Steel Industrial Research Council, in the work of which he took particular interest, and he sat on many of the Technical Committees of the British Standards Institution. His war-time appointments included the Chairmanship of the Advisory Committee of the Iron and Steel Control and membership of a Mission sent to America by the Ministry of Supply in 1942. He was also a Member of the following scientific and technical bodies :

> Advisory Committee of the National Physical Laboratory.
> Iron and Steel Industrial Research Council and Council of the British Iron and Steel Research Association.
> Institution of Automobile Engineers.
> Institute of Fuel.
> Institute of Metals.
> Verein deutscher Eisenhüttenleute.
> American Society for Metals.
> American Institute of Mining and Metallurgical Engineers.
> Preliminary Council of the Institution of Metallurgists.

Dr. Swinden was an active member of three of the four Joint Research Committees of The Iron and Steel Institute and Chairman of several Sub-Committees. On the death of Dr. W. H. Hatfield, F.R.S., he was appointed Chairman of the Committee on the Heterogeneity of Steel Ingots, of the Alloy Steels Research Committee, and of the Corrosion Committee. His work as Chairman of the Oxygen Sub-Committee of the Committee on the Heterogeneity of Steel Ingots, in which he was particularly interested, won wide acknowledgment.

He received the M.C. James Gold Medal for a paper published in the *Transactions* of the North-East Coast Institution of Engineers and Shipbuilders, and was presented with the Silver Medal of the Institution of Marine Engineers.

Dr. Swinden was elected a Member of The Iron and Steel Institute in 1910 and a Member of Council in 1935. In 1944 he was made a Vice-President. When he was presented with the Bessemer Gold Medal in 1941 in recognition of the value of his original investigations into the metallurgy of steel and of his eminent services to the organization and direction of research in the steel industry, he said, in reply, " A Prime Minister once wrote, ' Rational industrious useful beings are divided into two classes : Those whose work is work and whose pleasure is pleasure and those whose pleasure and work are one. Fortune has favoured those who belong to the second class.' In that respect I count myself fortunate."

The Rt. Hon. Lord Airedale of Gledhow died on March 11, 1944, at Stanstead, Essex, at the age of eighty. Born on October 7, 1863, he was the eldest son of the late Sir James Kitson, first Baron Airedale of Gledhow. Albert Ernest Kitson (as he then was) was educated at Rugby and at Trinity College, Cambridge, and as a young man entered the Airedale Foundry and the Monk Bridge Iron and Steel Works founded by his father. Like his father, who was President of The Iron and Steel Institute from 1889 to 1891, he became a Member of the Institute early in his career (in 1889); in 1912 he was elected a Member of Council and in 1923 Vice-President; three years later he became an Honorary Vice-President. Lord Airedale was interested in mineral resources and wrote two monographs on the subject : " The Economic Minerals and Rocks of Victoria " in 1906, and " Outline of the Mineral and Water-Power Resources of the Gold Coast " in 1925.

He was for some years a Member of the Court and Council of the University of Leeds. He succeeded his father as Second Baron in 1911.

Colonel Sir MAURICE HUGH LOWTHIAN BELL, Bt., C.M.G., T.D., died on November 17, 1944, at the age of seventy-three. Educated at Eton, in France and in Germany, he joined the family business of Messrs. Bell Brothers, Ltd., of Middlesbrough, iron-masters, in 1893. When that firm was merged into Messrs. Dorman, Long and Co., Ltd., he became a member of the Board of that Company, a position which he retained until his death.

Sir Maurice took part in the South African War in 1900, was promoted Honorary Captain in 1901, was Lieutenant-Colonel of the 4th Battalion Yorkshire Regiment (Green Howards) from 1913 to 1917, with whom he took part in many battles in Flanders, and in 1927 was promoted to Honorary Colonel of the 4th Green Howards. He was a keen sportsman.

He also took an active interest in civil affairs and was appointed a magistrate, a Deputy-Lieutenant for the North Riding, and Sheriff of Durham (1921). Sir Maurice had a real interest in the welfare of young people and held several official positions in youth organizations, being a member of the North Riding Youth Committee, Chairman of the Joseph Walton Boys' Club in Middlesbrough, and Chairman of the George Edwards Boys' Club in South Bank.

Sir Maurice, who was elected a Member of The Iron and Steel Institute in 1906, a Member of Council in 1927 and an Honorary Vice-President in 1934, was the son of the second baronet, the late Sir Hugh Bell, and grandson of Sir Lowthian Bell, both of whom had been Presidents of the Institute.

ROBERT ARMITAGE died at his home, Farnley Hall, Leeds, on February 10, 1944, at the age of seventy-eight. He was educated at Westminster School and Trinity College, Cambridge, and in 1889, when he was twenty-three, was called to the Bar by the Inner Temple. He first became associated with Messrs. Brown Bayley's Steel Works, Ltd., in 1888, at a time when the industry was suffering badly from the slump which followed the Franco-German war. In 1890 he became a Director and in 1895 Chairman, a position that he held until his death. Mr. Armitage also held directorates of several other Yorkshire firms; these included the Yorkshire Electric Power Co., Ltd., Brodsworth Main Colliery Co., Ltd., Doncaster Collieries Association, Ltd., Electrical Distribution of Yorkshire, Ltd., Hickleton Main Colliery Co., Ltd., Markham Main Colliery, Ltd., the Wagon Finance Corporation, Ltd., and the Hoffman Manufacturing Co., Ltd.

Mr. Armitage had a notable public career; from 1904 to 1905 he was the Lord Mayor of Leeds and for the subsequent three years Deputy Lord Mayor; from 1906 to 1922 he represented the Central Division of Leeds in the House of Commons.

He was elected a Member of The Iron and Steel Institute in 1898.

Dr. GUY DUNSTAN BENGOUGH, F.R.S., died on January 20, 1945, at St. Leonards-on-Sea, at the age of sixty-eight. He was the son of the late Major E. B. Bengough of Chislehurst and received his education at Malvern, Selwyn College, Cambridge, and at the Royal School of Mines. After spending several months in the late Sir William Roberts-Austen's research laboratory at the Royal Mint, he was appointed lecturer in metallurgy and demonstrator in chemistry at the Sir John Cass Technical Institute, London, where he remained for two years, resigning his position to become metallurgist and assayer of gold and tin ores to a tin syndicate in Burma. On his return to England he was appointed to the Metallurgical Department of Birmingham University, after which, in 1907, he became lecturer in metallurgy at the University of Liverpool, where he became interested in the corrosion of metals. About 1910 he was appointed investigator of corrosion to The Institute of Metals and he

carried out investigations on the annealing of metals and on the tensile properties of metals and alloys at high temperatures. In 1911 he published the first of a series of reports to the Corrosion Research Committee of that Institute. This series dealt mainly with the corrosion of condenser tubes, but was also concerned with the general problem of corrosion. A second report, written in collaboration with R. M. Jones, was published in 1913. Shortly after the outbreak of war in 1914 Dr. Bengough was gazetted to the Royal Garrison Artillery, and during 1915–16 was Captain and Adjutant to the Commandant, Royal Artillery, Mersey Defences. In 1916 he was seconded for research work at the request of the Admiralty; in 1919 he presented a fourth report to the Corrosion Committee in collaboration with Dr. O. F. Hudson (a third report having been published in 1916 by W. E. Gibbs and R. H. Smith). On returning to civil life, Dr. Bengough was appointed chief investigator to the previously mentioned Corrosion Committee and continued in this capacity until 1924, when, following a fifth report (1920) and a sixth (1922) a seventh report was published in collaboration with R. May. On leaving the service of The Institute of Metals in 1924, Dr. Bengough took up an appointment under the Department of Scientific and Industrial Research and, two years later, published, in conjunction with J. M. Stuart, an account of the now well-known anodic-oxidation process for the protection of aluminium and certain light alloys against corrosion. In 1927 Dr. Bengough was appointed Principal Scientific Officer at the Department's Chemical Research Laboratory, Teddington, where he was placed in charge of the Corrosion Research Section. In 1928 he lectured on corrosion before the Eighth Congress of Industrial Chemistry, held at Strasbourg, and about that time he was invited to write the article on corrosion for the *Encyclopœdia Britannica*. In collaboration with J. M. Stuart and A. R. Lee, Dr. Bengough presented a series of papers to the Royal Society on the theory of corrosion in the light of quantitative measurements. For his work in this field he received a Beilby Memorial Award in 1930 and was elected a Fellow of the Royal Society in 1938. In addition to the papers enumerated above he published others in a number of periodicals and proceedings; the following were contributed to The Iron and Steel Institute :

" The Action of Sea-Water on Mild Steel " (with A. R. Lee, *Journal*, 1932, No. II.).
" The Design, Interpretation and Uses of Standard Corrosion Tests in Salt Solutions and Industrial Waters—Parts I. and II." (with F. Wormwell, Third and Fourth Reports of the Corrosion Committee, 1935 and 1936).

Dr. Bengough retired shortly after the outbreak of war in 1939 and then acted as consultant to the Chemical Research Laboratory, Teddington. He was a Member of the Corrosion Committee of The Iron and Steel Institute and in June 1941 was appointed Scientific Advisor. He was Chairman of the Marine Corrosion Sub-Committee and a member of the Laboratory (Corrosion) Research Sub-Committee. Dr. Bengough was a distinguished scientist whose contributions to the knowledge of the mechanism and prevention of the corrosion of iron and steel are of outstanding and permanent value.

Dr. Bengough had been a Member of the The Iron and Steel Institute since 1908.

Sir JOHN WYNDHAM BEYNON, Bt., C.B.E., D.L., died on October 13, 1944, at his home at Newport, Monmouthshire, aged seventy-nine. Educated at Clifton College, Bristol, and then abroad, he returned to Monmouthshire to become one of the leading industrialists of the County. As Chairman of the Ebbw Vale Steel, Iron and Coal Co., Ltd., he successfully

negotiated, in 1935, the merging of this Company with Messrs. Richard Thomas and Co., Ltd. At his death he was Chairman of Messrs. T. Beynon and Co., Ltd., and the Aberthaw and Bristol Channel Cement Co., Ltd., and Chairman and Joint Managing Director of Fernhill Collieries, Ltd. Sir John did much during his career to develop Newport as a harbour.

From 1917 to 1918 he was the High Sheriff of Monmouthshire, and in 1920 was made a C.B.E.; in the same year he was created a Baronet.

Sir John was elected a Member of The Iron and Steel Institute in 1917.

HENRY ALOYSIUS DAVIES, J.P., died on November 25, 1944, at the age of seventy-one. He joined the Patent Shaft and Axletree Co., Ltd., at the age of fourteen, and after serving in various departments of the Brunswick Steelworks of this Company, he became Works Manager and later General Manager. Mr. Davies was a member of the Birmingham Iron Exchange, a Member of the Council and Executive Committee of the British Iron and Steel Federation, Chairman of the Wednesbury Hospital Saturday Fund, and President of the Wednesbury Nursing Institution. He was a member of the Wednesbury Borough Council for eleven years and was appointed a borough magistrate in 1925. In 1937, when Mr. Davies had completed fifty years' service with the Patent Shaft and Axletree Company, his name was added to the roll of Honorary Freeman of the Borough of Wednesbury.

On the day before his death Mr. Davies attended a meeting of the West Midlands Joint Electricity Board, of which he had been a member since its inception.

Mr. Davies became a Member of The Institute in 1905.

AXEL MAGNUS E. F. FORNANDER died on July 29, 1944, at the age of sixty-eight. Born at Mönsterås in Sweden, he was educated at Kalmar secondary school, on leaving which he entered a bank, but he stayed there only a short time before becoming a book-keeper for Mackmyra Bruk for two years, followed by three years in a similar position with the Forsbacka ironworks. He then studied for a year at the Filipstad School of Mines, after which he spent several years as draughtsman at the Forsbacka works. In 1904 he received a travelling scholarship from the Swedish Chamber of Commerce to enable him to study in the United States. Returning to Sweden he continued his career with the Forsbacka Company, where his skill and knowledge gained him rapid advancement, for he was their rolling-mill engineer from 1904 to 1907, chief engineer from 1907 until 1920 and Managing Director from 1920 to 1924, when he was offered a directorship with Fagersta Bruks Aktiebolag, a position which he accepted and held until 1942.

In the course of an active life, and it can truly be said that his life story is the story of half a century of Swedish iron production, Mr. Fornander acquired interests in many Swedish industrial concerns, including iron and steel works, mines and engineering firms. That such a man came to be respected and his advice sought in spheres extending far beyond the concerns with which he was directly associated was only to be expected, and that this was so is shown by the honorary positions he was asked to fill and the honours which were bestowed upon him. He was made a Member of Council of Jernkontoret in 1927, was elected Chairman of the Council in 1942 and was awarded their Gold Medal in the same year; he was also Chairman of their Technical Advisory Committee for twelve years. The other Swedish and foreign orders and honours he received included : Knight of the Royal Order of the North Star (1933); Pro Patrias Grand Gold Medal (1941); Knight Commander of the Royal Order of Vasa, First Class (1942); Member (1938) and Honorary Member (1941) of the Engineers' Academy of

Science. Finland made him a Knight Commander of the Order of the White Rose in 1940, and he was also elected an Honorary Member of the Verein deutscher Eisenhüttenleute in 1937.

He became a Member of The Iron and Steel Institute in 1922.

FREDERICK FLEMING McINTOSH died on February 23, 1944, at Sewickley, Philadelphia, after a short illness. He was connected early in his career with the Crucible Steel Company and the Bethlehem Steel Company; later he was appointed Assistant Professor of Metallurgy at the Carnegie Institute of Technology. In 1926 he returned to the Crucible Steel Company as Chief Metallurgist and was appointed Director of Metallurgy in 1939, which position he occupied at the time of his death.

Mr. McIntosh was elected a Member of The Iron and Steel Institute in 1926.

Dr. BERAM D. SAKLATWALLA died in an aeroplane accident in California on November 4, 1944. Born in Bombay in 1881, he obtained his B.Sc. from the University of that city in 1901 and a Doctorate of Engineering from the Royal Polytechnic Institute, Charlottenberg, Berlin, in 1908. He came to the United States in the following year and joined the newly organized American Vanadium Company of Pittsburgh. In 1910 he was made General Superintendent of the Vanadium Corporation of America, and from 1919 to 1935 was Vice-President and Director of Research of that Corporation. From 1938 until his death he was Chairman of the Board of the Alloys Development Corporation, Pittsburgh, and consultant to a number of companies.

More than 130 patents were taken out by him during his career. His most important recent work was in connection with the development of a series of low-alloy high-tensile steels which are now being manufactured by several companies. In 1924 the Society of Chemical Industry awarded the Grasselli Medal to Dr. Saklatwalla, and, in 1942, he delivered the Richards Memorial Lecture before the Electrochemical Society in New York.

He was elected a Member of The Iron and Steel Institute in 1911.

Professor ALFRED STANSFIELD died at Montreal on February 5, 1944. Born at Bradford, Yorkshire, in 1871, he was educated at Ackworth School, Pontefract, and at the Bradford Technical School. In 1888 he obtained a scholarship at the Royal School of Mines, where he studied under the late Sir William Roberts-Austen. Three years later he graduated with honours in metallurgy and became an Associate of the Royal School of Mines. He then worked for seven years in the private laboratories of Sir William Roberts-Austen at the Royal Mint and subsequently gained the B.Sc. and D.Sc. degrees of the University of London. In 1898 he was appointed a lecturer at the Royal School of Mines.

Between 1895 and 1900 Professor Stansfield made (under the direction of Sir William Roberts-Austen) a number of important contributions to the subject of pyrometric measurement, the results of his work being reported by the Alloys Research Committee of the Institution of Mechanical Engineers. His most striking contributions to physical metallurgy, however, were contained in two papers published by The Iron and Steel Institute in 1899 and 1900, respectively, namely :

" The Present Position of the Solution Theory of Carburised Iron " (*Journal*, 1899, No. II.).
" The Present Position of the Solution Theory of Carburised Iron.—Part II." (*Journal*, 1900, No. II.).

In these papers the problems involved in the understanding of the relations between carbon and iron within the ranges covered by steel and cast iron are clearly enunciated.   In 1901 Professor Stansfield was awarded a grant from the Andrew Carnegie Research Fund by The Iron and Steel Institute and, as a result of the researches carried out under this award, the following paper was published by the Institute in 1903 :

" The Burning and Overheating of Steel " (*Journal*, 1903, No. II.).

Professor Stansfield was appointed Professor of Metallurgy and Head of the Department at McGill University, Montreal, in 1901 ; there he conducted researches on the electric smelting of zinc and iron ores.   In 1914 he visited Sweden on behalf of the Canadian Government in order to report on the methods used there for the electric smelting of iron ores. In 1915 he served on a commission set up by the Canadian Minister for Militia and Defence to investigate the possibilities of producing refined copper and zinc in Canada, and in 1918 submitted a report to the Government of British Columbia on the feasibility of the electric smelting of the magnetite ore found in that country.

As a result of his researches at McGill University his books entitled " The Electric Furnace : Its Construction, Operation and Uses " and " The Electric Furnace for Iron and Steel " were published in 1914 and 1923, respectively, in London and New York.

Professor Stansfield was an active member of many scientific and technical societies in Canada and the United States and eventually became a Fellow of the Royal Society of Canada.   In 1936 he retired from his post at McGill University and was made Professor Emeritus of Metallurgy.

He was elected a Member of The Iron and Steel Institute in 1899.

Professor ENRIQUE A. TOUCEDA died on October 20, 1944, in Albany, New York State, at the age of seventy-seven.

Professor Touceda, who was an acknowledged authority on malleable iron castings, was born in Cuba.   In 1887 he graduated from the Rensselaer Polytechnic Institute, Troy, New York State, with a degree in civil engineering, and joined the Troy Iron and Steel Company.   In 1898 he went into business on his own as a consulting metallurgical engineer.   A few years later he returned to the Rensselaer Polytechnic Institute as Professor of Metallurgy.   In 1912 he was engaged by the American Malleable Castings Association (now the Malleable Founders' Society) as a consultant.   Professor Touceda's numerous papers on malleable castings are well known to readers of the American technical press and his activities in the technical affairs of the American Foundrymen's Association were no less considerable.   He was an Honorary Member of the Institute of British Foundrymen as well as a member of many scientific and technical societies in the United States.

Professor Touceda was elected a Member of The Iron and Steel Institute in 1923.

ERNST BIANCO WESTMAN died on April 15, 1944, at Kenley, Surrey, after a short illness.   Born in Sweden in 1859, he came to live in London in 1883.   In 1887 he started business on his own in London as an importer of Swedish iron ore.   Later, the business grew and he became Joint Managing Director of the firm now known as Messrs. Ernst B. Westman, Ltd.

He was elected a Member of The Iron and Steel Institute in 1905.

SECTION II.

A SURVEY OF LITERATURE ON THE MANUFACTURE AND PROPERTIES OF IRON AND STEEL, AND KINDRED SUBJECTS.

CONTENTS.

Abstractors and translators : Mr. R. A. RONNEBECK and Dr. D. R. STEINER.

REFRACTORY MATERIALS

Steel Plant Refractories Problems. L. A. Smith. (Blast Furnace and Steel Plant, 1944, vol. 32, Jan., pp. 104-108). Some problems relating to refractory bricks and insulating material in blast-furnaces, steel furnaces and soaking pits are discussed. The suggestions are made that special shapes are too often required and that the steel industry of the United States should set up its own central research organisation to conduct research on refractories.

Open-Hearth Construction with Basic Brick. H. M. Griffith. (Blast Furnace and Steel Plant, 1944, vol. 32, Jan., pp. 83–84). Some experiences with basic linings in open-hearth furnaces are related. In Canada there is a 50-ton furnace which is all basic at one end as far as the junction of the main roof and the port slope. Thus the port slope, port roof, side walls, port ends, uptake walls and slag-pocket arch are all of basic material, whilst the main roof and opposite end of the furnace are of silica brick for comparison. This furnace has been in operation since January 1943, and except for a partial port roof repair and the renewal of sections of the side walls and port end, the basic end is still intact after over 700 heats, whereas the silica end has had one complete rebuild and two minor repairs. The initial cost of the basic end was four times that of the silica end, but there is a great saving in labour for repairs and slag removal.

FUEL

Steam in Steelworks. G. Graham. (Iron and Steel, 1944, vol. 17, Mar., pp. 277–283). Recommendations are made for saving fuel in steelworks boiler plants. These include : (1) Testing the brickwork with a naked flame to discover cracks through which cold air is drawn ; (2) provision of ample insulation on all surfaces radiating heat ; (3) examination and replacement of seating blocks ; (4) regular removal of dust from flue tubes and of scale from inside the boiler ; (5) availability of proper firing tools ; and (6) preventing wastage of heat from bare pipes.

Furnace Control Operated from the Load Temperature. O. G. Pamely-Evans. (Metallurgia, 1944, vol. 29, Feb., pp. 171–175). The efficiencies of two methods of furnace control operated by the load temperature are compared. These are the " on-off " and the " proportional " methods as applied to radiant-tube furnaces. In proportional control there is a " throttling band " or range of temperature over which the valve gear operates, the mid-point of the

band corresponding to the predetermined temperature setting. Typical time-temperature curves for the heating-up and holding periods with the two methods of control are reproduced and are analysed mathematically to show that the heat consumption is less with proportional control.

Thermobloc Recuperators and Heat Exchangers. (Metallurgia, 1944, vol. 29, Mar., pp. 261–263). A description of the " Thermobloc " metal recuperator is given (*see* Journ. I. and S.I., 1944, No. I., p. 40 A).

Fuel Economy at Coking Plants. G. E. Foxwell. (Coke and Smokeless-Fuel Age, 1944, vol. 6, Mar., pp. 52–54). The economics of fuel consumption and costs for heating coke-ovens with coke-oven gas and with producer gas generated from coke are discussed, and the question is asked whether the coking industry should endeavour to save gas at the expense of coke, or to save coke at the expense of gas. Some points in the first Fuel Efficiency Bulletin issued by the Coking Industry Committee of the Ministry of Fuel and Power are critically reviewed.

Reclaiming Sulphur from Coke-Oven Gas. (Steel, 1944, vol. 114, Feb. 7, pp. 143, 179). **Sulphur Extracted from Coke-Oven Gas by the Ammonia Thylox Method.** (Blast Furnace and Steel Plant, 1944, vol. 32, Jan., pp. 119–120). A brief description is given of the Thylox sulphur recovery plant at the Ford Motor Company's works at Dearborn, where 54,000,000 cu. ft. of coke-oven gas are treated every 24 hr. The sulphur in the gas is in the form of hydrogen sulphide, which dissolves in the Thylox solution in the scrubbing tower. This solution is then treated with oxygen in a manner which causes a sulphur slurry or froth to form. The sulphur is separated from this by heating in an autoclave to 240° F.

PRODUCTION OF IRON

Blast Furnace Moisture Control. J. J. Alexander. (Blast Furnace and Coke Oven Association of the Chicago District and the Eastern States Blast Furnace and Coke Association : Iron and Steel Engineer, 1944, vol. 21, Feb., pp. 38–41). *See* Journ. I. and S.I., 1944, No. I., p. 145 A.

Effect of Good and Bad Coke on Blast Furnace Operation. C. J. Rice. (Blast Furnace and Steel Plant, 1944, vol. 32, Jan., pp. 101–103). The operation of a blast furnace with a bad coke containing 22% of ash and with a good coke containing 5–10% of ash is described. The chemical composition of the coke ash has much to do with the coke not burning well at high blast temperatures ; a coke ash that does not fuse before the carbon around it is burned away will withstand higher blast temperatures than an ash which fuses easily.

Swedish Sponge Iron. E. Améen. (Iron Age, 1944, vol. 153, Jan. 20, pp. 55–59, 150 ; Jan. 27, pp. 56–65). An account is given of the Wiberg process of manufacturing sponge iron as it has been successfully developed at Söderfors in Sweden. The paper is an abridged translation of that which appeared in Jernkontorets Annaler, 1943, vol. 127, No. 8, pp. 277–315 (*see* Journ. I. and S.I., 1944, No. I., p. 7 A).

FOUNDRY PRACTICE

Cold-Blast Irons Duplicated by Synthetic Mixtures. J. E. Hurst. (Iron Age, 1944, vol. 153, Feb. 17, pp. 74–76). In order to match the specific properties of a given type of cold-blast iron, the procedure followed was first to determine the chemical analysis and the complete mechanical properties of the particular brand or consignment of iron required to be matched. With this information available, a mixture was devised from the various materials in stock, of which the chemical analyses and mechanical properties were determined. The mixture was calculated to give a mean chemical and mechanical analysis closely approximating that of the iron to be duplicated. The success of this procedure relies on the assumption that the differences in properties of mixed materials survive remelting. Experiments and tests are described which prove that the whole of the known characteristics, including the chilling properties, of cold-blast irons can be completely duplicated by this procedure.

Production Results with a Basic Lined Cupola. C. Heiken. (Foundry Trade Journal, 1944, vol. 72, Mar. 2, pp. 185–187, 190). An English translation is presented of a paper in Giesserei, 1934, vol. 21, Oct. 26, pp. 453–456, describing the operation of a basic-lined cupola with a dolomite and fluorspar slag for melting iron for subsequent refining in the converter to make steel castings (*see* Journ. I. and S.I., 1934, No. II., p. 542).

Cupola Operation and Control. R. C. Tucker. (Institute of British Foundrymen : Foundry Trade Journal, 1944, vol. 72, Feb. 17, pp. 135–139). Theories and calculations relating to cupola blast control are presented and discussed. It is generally agreed that rectangular tuyeres with a total cross-section area equal to one-quarter of the hearth area give the best results. The disadvantages of blast control by pressure are illustrated by two examples : (1) If a cupola is blown by a positive blower with a rheostat control set at a mark found by experience, and some factor such as sticky slag, small coke or scrap becomes operative, the blast pressure will rise ; this slows down the blower, and the volume of air supplied decreases, with consequent loss of production ; and (2) if the blast is supplied by a fan blower and the same defect in

operation occurs, the pressure does not alter, but the fan delivers less volume and the output falls without the pressure gauge giving any warning. The only sure way of controlling the air supply is to measure its volume; with a positive blower this can be done by obtaining records of the changes in both blast pressure and current consumption of the blower.

Control of Cast Iron. W. Lathrop. (Canadian Metals and Metallurgical Industries, 1944, vol. 7, Jan., pp. 12–16). Recommendations are made on the use of rapid chill tests and ladle additions to enable the small jobbing foundry to improve the quality of the castings produced.

Cupola Lighting. (Iron and Steel, 1944, vol. 17, Mar., p. 296). A brief illustrated description is given of a portable gas torch specially designed for lighting cupolas. The torch burns town gas in combination with a separate low-pressure air supply from the cupola blower.

Design of a Front Slagging Cupola Spout. R. D. Petcher. (Transactions of the American Foundrymen's Association, 1944, vol. 51, Mar., pp. 706–708; American Foundryman, 1944, vol. 6, Jan., pp. 7–8). A special cupola spout is described in which the molten metal and slag flowing from the taphole pass into a trough, the metal flowing under a slag dam and over the lip of the spout into a receiver, from which it is distributed by transfer ladles to the moulding floors. The slag runs from a spout at one side just behind the dam into a slag ladle.

Quality Control in High Duty Iron Production. E. W. Harding. (Institute of British Foundrymen: Foundry Trade Journal, 1944, vol. 72, Mar. 16, pp. 219–223; Mar. 23, pp. 239–242; Mar. 30, pp. 265–270). Measures adopted to control quality in the production of Meehanite cast iron are described and discussed. The following key control points are established: (1) Control over raw materials; (2) control over charging practice, which includes composition and weights; (3) ladle control; and (4) control over combustion conditions. It is better to assess the standard of control by the test values obtained for the final product than by the degree of application of the various key controls. The use of frequency curves to study test results and of control charts for average and standard deviations from mean results is explained with examples.

Steel Melting Practice. J. Preston. (Institute of Australian Foundrymen: Foundry Trade Journal, 1944, vol. 72, Mar. 9, pp. 199–203). In Melbourne the crucible furnace, the side-blown converter and the electric furnace lined with either acid or basic refractories are all used. Crucibles are used for melting expensive alloy steels usually only required in small quantities. The cupola/ side-blown-converter practice is described in detail. When cupola and converter are operating efficiently, steel can be poured every 20 min. At one plant the blast is put on the cupola at 11.45 a.m., and the first heat is in the converter 40 min. later; the first

blow of the day takes about 15 min., and sixteen blows are completed by 5 p.m. Whilst the basic electric furnace is metallurgically supreme for reducing the phosphorus and sulphur contents, it has certain drawbacks in Melbourne, where magnesite is expensive, the bricks costing about 2s. each. Due to the fluxing action of lime dust, the life of the silica walls and roof is only one-quarter of that of the acid furnace. For manganese steel, the basic electric furnace is much the best, but for ordinary steel castings the Melbourne foundries are fully justified in maintaining the converter process.

New Steel Foundry Makes Navy Castings. P. Dwyer. (Foundry, 1943, vol. 71, Nov., pp. 114–117, 194–195; Dec., pp. 112–115, 205–207). An illustrated description is given of the new steel foundry recently erected for the Birdsboro Steel Foundry and Machine Company, at Birdsboro, Pennsylvania. This foundry is designed for a production of 3000 tons of castings per month. The steel is made in two 50-ton basic oil-fired furnaces. A large area in the building is devoted to sand preparation, and the Randupson system of mould-making is followed.

Modern Steel Making. (Electrical Review, 1944, vol. 134, Mar. 10, pp. 326–330). A description is given of a self-contained foundry for the mass production of small steel castings, special attention being directed to the electrical machinery. The plant comprises two cupolas, a horizontal furnace supported on rollers and fired by pulverised coal, two converters for preparing the steel, and a separate fettling shop. Particulars are given of the motors used for moving materials, driving the blowers and many other purposes.

The Chemical and Physical Reactions in the Blowing of Small Steel Converters. W. Goldsbrough and S. G. Throssell. (British Steelmaker, 1944, vol. 10, Jan., pp. 12–15). The reactions in the blowing of small converters are discussed under the headings : (a) The composition of the iron to be charged ; (b) the oxidation reaction ; (c) the oxidation products ; (d) the formation of flame, smoke and sparks during blowing ; (e) the ejections ; and (f) the composition of the slag.

The Blowing of Small Steel Converters. II. The Determination of the Dimensions and the Blast Supply. W. Goldsbrough and S. G. Throssell. (British Steelmaker, 1944, vol. 10, Apr., pp. 145–147). As a supplement to an earlier paper on the chemical and physical reactions in small steel converters (*see* preceding abstract), the present paper offers methods of calculating : (a) The dimensions of a 2-ton side-blown converter given the bath depth ; (b) the blast supply ; (c) the blower capacity ; (d) the diameter of the blast main ; (e) the blast pressure ; (f) the power required for blowing ; and (g) the total tuyere area.

Semi-Steel as an Engineering Material. (Mechanical World, 1944, vol. 115, Jan. 28, pp. 87–88). Methods of making cast irons of the " semi-steel " class containing 2–2·5% of carbon are briefly

described. Its production involves a means of melting which allows accurate control of composition and an adequate reserve of heat for superheating before casting. One method is to make a heat of carbonless steel in a small foundry converter and to add the proper proportion of this exceedingly hot metal to the main body of iron in the ladle. Another method is to add a ferro-silicon/ nitrate mixture to the ladle of liquid iron ; this reacts in a similar manner to thermit powder with the generation of great heat. These two methods suffer from the relative inability to make use of much steel scrap. The application of the arc furnace overcomes these difficulties. It can be used in two ways, depending on economic conditions and available raw material. It may be acid lined if simple melting and dilution only are practised with reasonably pure raw material. Basic lined furnaces can be used where a pre-liminary purification of the scrap has to be undertaken. The casting technique is similar in each case. Once the composition has been adjusted, the whole charge is rapidly superheated to about 1600° C. and poured into the ladle. Here it is held quiescent until it cools to normal casting temperature.

The Sulzer Type Cast-Steel Methane Containers. M. Roš. (Eidgenössische Materialprüfungs- und Versuchsanstalt für In-dustrie, Bauwesen und Gewerbe, Zürich, Dec., 1943, Report No. 147). A description is given of the cast-steel container with a capacity of 1·1 cu. m. which was developed at the Sulzer works for storing methane at a pressure of 350 at. and a maximum tem-perature of 50° C. The container is 3 m. long and 730 mm. in inside dia. ; the wall tapers from 80 to 90 mm. in thickness. Details of the casting technique, heat treatment and tests are given.

Heavy Gray Iron Castings Produced by Modern Controlled Methods. S. Appelby. (Transactions of the American Foundry-men's Association, 1943, vol. 51, Dec. pp. 487–498). The produc-tion of castings up to 125 tons in grey iron by the Buffalo Foundry and Machine Company is described. A new system for preparing synthetic sand was introduced ; this included a sand storage pit for all shake-out sand from moulds and cores, a complete sand reclamation and salvage unit with control of the removal of fines, a sand-preparation unit and a sand-testing laboratory. One facing-sand mixture and one heap-sand mixture have been standardised as a result of this system, and they are applied to all classes of work in dry sand or loam. One grade of high-quality blacking has also been standardised. Large moulds are dried by portable driers burning gas and air. Three cupolas with a total melting capacity of 45 tons per hr. are available. Pouring temperatures range from 1370° to 1480° C., and the desired pouring temperature for each casting is predeter-mined. The pouring speeds are regulated to deliver hot metal into the pit moulds at 10–15 tons per min.

Slip Coated Synthetic Foundry Sand. F. Singer. (Foundry Trade Journal, 1944, vol. 72, Mar. 30, pp. 261–264; Apr. 6, pp. 285–288). Experiments in the bonding of foundry sand with clay in the form of a colloidal casting slip as used in ceramics are described. From the results it appears to be established that : (1) The conversion of the clay bond into a true colloidal " casting slip " (in the ceramic sense) permits the complete covering of each particle of sand with a thin layer of clay within a very short mixing period and without introducing an excess of water. (2) Owing to the fluidity and low cohesion of the liquefied clay, the sand thus bonded can easily be rammed to give very high dry-strength figures approaching those obtained with bentonite-bonded sand ; but the green-strength figures are rather low, as could be expected from the lack of cohesion between the deflocculated clay particles. (3) If the deflocculated clay coating is subsequently reflocculated, the green strength rises to very high values, substantially above those obtained with raw clay by prolonged mixing. The dry-strength figures are, however, very much lowered. (4) An addition of flocculants to sand bonded with raw clay also raises the green strength. The various raw clays are obviously in varying intermediate states of flocculation, and can probably be made more suitable for their purpose by additional flocculation or deflocculation, as the case may be. The adaptability and usefulness of domestic bond clays, and even of naturally bonded sands, could be considerably extended thereby. (5) The deflocculation, the reflocculation and the mixing in general are best carried out in a specialised non-crushing mixing machine of the type in which all the mixing work is done between the paddles, and not between the paddles and the pan.

Tests for Pattern Coating Substitutes for Shellac. F. C. Cech. (Transactions of the American Foundrymen's Association, 1944, vol. 51, Mar., pp. 732–734). This paper is supplementary to an earlier one entitled " Coatings for Wood Patterns " (*see* Journ. I. and S.I., 1941, No. I., p. 46 A) ; it reports the results of drying-time and abrasion tests on five proprietary brands of pattern coating containing substitutes for shellac.

A Small Moulding Unit. A. Wood. (Institute of British Foundrymen : Foundry Trade Journal, 1944, vol. 72, Mar. 2, pp. 175–179). A layout of foundry equipment is described by which a jobbing foundry with a floor space of about 48 ft. × 26 ft. can be converted to mass production.

Use of Cement in Foundry Molding. C. A. Sleicher. (Transactions of the American Foundrymen's Association, 1944, vol. 51, Mar., pp. 737–747). The advantages of using cement as a binder for moulds and cores are discussed. Cement can be used for positions where the iron shrinks away from the mould or core, *e.g.*, for the side, bottom and cover cores of lathe-bed castings. No fuel is needed for drying cement moulds, and the labour and crane

power for moving moulds and cores to and from drying ovens are saved. A good mix consists of white silica sand 89% and quick-drying cement 11%, to which 6% by volume of water is added ; the drying time is about 72 hr.

The Production of Cast-Iron Pipes. W. Phillips. (Institute of British Foundrymen : Foundry Trade Journal, 1944, vol. 72, Mar. 9, pp. 207–208). Suggestions are made, based on South African foundry practice, for reducing the cost of manufacture of cast-iron pipes. An entirely mechanised plant is eminently satis-factory for producing $3\frac{1}{2}$-in. and 4-in. dia. pipes ; the layout of such a plant having two sand-slingers and of a plant designed to do only the moulding and core-making by mechanical means is described. The present manual methods for making the smaller sizes could be improved by allocating a separate job to each man and introducing a stripping plate machine.

New Gray Iron Foundry Makes Machine Tool Castings. W. G. Gude. (Foundry, 1944, vol. 72, Jan., pp. 112–115, 195–198). An illustrated description is given of the new grey iron foundry at the works of the Landis Tool Company, Waynesboro, where castings for precision grinding machines are made.

Core Blowing as a Factor in a Semi-Production Foundry. Z. Madacey. (Transactions of the American Foundrymen's Associa-tion, 1944, vol. 51, Mar., pp. 593–612). The organisation of the sand-control and core-blowing department of the Caterpillar Tractor Company is described and illustrated.

Making Cores for the Steel Casting. S. W. Brinson and J. A. Duma. (Transactions of the American Foundrymen's Association, 1944, vol. 51, Mar., pp. 563–589). A description is given of the methods of making cores for large steel castings developed at the Norfolk Yard of the United States Navy. Particular reference is made to the use of " arbors " or re-enforcing rods for supporting the cores.

PRODUCTION OF STEEL

Californian Iron and Steel Plant. (Engineer, 1944, vol. 177, Feb. 25, pp. 148–149). Brief particulars and some illustrations are given of the iron and steel plant of the Kaiser Co., Inc., recently completed at Fontana in California. It consists of one 1200-ton-per-day blast furnace with auxiliary equipment and sintering plant, a coke-oven plant with 90 ovens, a tar-distillation plant, six 185-ton open-hearth furnaces, a 110-in. plate mill, a 28-in. structural mill and a merchant bar mill.

Steel Melting Processes. V. Electric. (British Steelmaker, 1944, vol. 10, Apr., pp. 150–155). Some advantages of the electric furnace for making steel and the true significance of the terms

" clean " and " dirty " as applied to steel are discussed. It is suggested that Izod impact test specimens should be cut so as to fracture along the grain to show the steel at its worst instead of at its best, as is the case when the fracture is across the grain.

The Modern Arc Furnace. T. J. Ess. (Iron and Steel Engineer, 1944, vol. 21, Feb., pp. 7-AF–58-AF). A comprehensive review of the construction and operation of modern electric arc furnaces in the United States is presented.

Successful Procedure Worked Out for Using More Alloy Scrap in Making Electric Furnace Steel. V. E. Zang. (Steel, 1944, vol. 114, Feb. 21, pp. 88, 110). The electric-furnace charging practice at a steel foundry where it was necessary to increase the proportion of scrap in the charge is described. The composition of the charge was in accordance with instructions from the laboratory, and these were based on analyses of the purchased scrap. When truck loads contained only one type of scrap, two samples were selected and duplicate analyses of each were made. If a truck load contained several types of scrap, two samples of each type were analysed and an average taken for all the results.

Electric Furnace Practice. W. J. Reagan. (Blast Furnace and Steel Plant, 1944, vol. 32, Jan., pp. 89–93). The working of electric-furnace heats to reduce the phosphorus and sulphur contents is described. Sulphur elimination under an oxidising slag proceeds by the formation of calcium sulphide in the slag. This sulphide does not form rapidly until the CaO/SiO_2 ratio exceeds 2 ; with a CaO/SiO_2 ratio of 3 to 3·5, the sulphur in the metal will be reduced by at least 0·01%, and often by 0·02%. The oxidising slag is removed after the carbon, sulphur and phosphorus have been worked down to the desired figure. A carbide slag is then formed by additions of burnt lime, sand and coke with fluorspar if required. This slag provides a neutral blanket under which the carbon and alloy content of the bath can be held fairly constant. Under this type of slag, which has little oxidising power, a recovery of 95% of the oxidisable alloying elements in the charge is possible.

Treatment and Refining of Metals in Electric Furnaces. W. Frick. (Swiss Technics, 1943, vol. 22, Nov.-Dec., pp. 15–19). A number of both large and small electric furnaces, of Swiss manufacture, for steel-making and heat treatment are described and illustrated.

The Constitution of Some Basic Open-Hearth Slags. B. Mason. (Iron and Steel Institute, 1944, this Journal, Section I). Fifteen samples of basic open-hearth slags were analysed chemically, and the phases present determined by a combination of methods—the examination of polished and thin sections, the determination of the refractive indices of silicate phases by the immersion method, the use of X-ray powder photographs, and in some cases by the actual separation of the phases present and their chemical analysis. The ratio $CaO/SiO_2(+ P_2O_5)$—the B value—ranged from 0·9 to

3·3.   The phases identified were olivine, CaO.RO.SiO$_2$ (R is used as a symbol for (Fe, Mn, Mg)) ; merwinite, 3CaO.MgO.2SiO$_2$; dicalcium silicate, 2CaO.SiO$_2$; tricalcium silicate, 3CaO.SiO$_2$; an oxide phase, RO ; dicalcium ferrite, 2CaO.Fe$_2$O$_3$; a magnetite phase, RFe$_2$O$_4$; a chromite phase, RCr$_2$O$_4$; and free iron.   The phase composition was correlated with the chemical composition, and the slags could be classified on the basis of the silicates present and the B values approximately as follows : $B = 0·9–1·4$, olivine slags ; $B = 1·4–1·6$, merwinite slags ; $B = 1·6–2·4$, dicalcium silicate slags ; $B > 2·4$, tricalcium silicate slags.

Robots and the Manpower Situation.   F. Mohler.   (Iron and Steel Engineer, 1944, vol. 21, Feb., pp. 47–57).   Examples are given of the application of amplidyne adjustable voltage control in many steel-making operations from the mining of ore to the inspection of finished steel.

FORGING, STAMPING AND DRAWING

Crossroll Forging at Christy Park.   A. F. Macconochie.   (Steel 1944, vol. 114, Feb 21, pp. 80–82, 112–114).   An account is given of the manufacture of shells at the Christy Park Works of the National Tube Company.   An Assel cross-roll mill plays the principal part in the piercing of the blanks ; its principles are explained.   The mill can be employed on all sizes from 3-in. to 155-mm. dia. blanks without changing rolls.

Forging 75-mm. Shell on Converted Rubber Presses.   A. B. Salkeld.   (Iron Age, 1944, vol. 153, Feb. 10, pp. 70–72).   A brief account is given of the reconditioned and adapted plant at a forging works where a rotary-hearth gas-fired furnace and two piercing and two drawing presses were installed.   The presses had previously been used for rubber manufacture, but they were successfully converted for making shells out of 3$\frac{1}{3}$-in. dia. billets.

Tools for Producing a Sheet Steel Pressing.   W. Danks.   (Machinery, 1944, vol. 64, Apr. 6, pp. 382–384).   The development of dies for piercing and pressing lock parts out of $\frac{3}{32}$-in. steel sheet is described and illustrated.

Improved Deep Drawing Process.   G. E. Stedman.   (Steel, 1943, vol. 113, Dec. 20, pp. 110–112).   A description is given of the sequence of operations in the manufacture of 37-mm. dia. steel cartridge cases from cold-coined cups.   The cup is drawn in five stages, and this is followed by tapering processes.   The material is also subjected to controlled annealing and etching between the draws ; the object of the etching is to roughen the surface so that it will hold lubricant during the next drawing operation.

Manufacture of 20-mm. Steel Cartridge Cases.   (Machinist, 1944, vol. 87, Mar. 11, Armament Section).   A detailed description

with drawings is given of the sequence of operations in the mass production of 20-mm. dia. steel cartridge cases as developed by the Dura Division of the Detroit Harvester Company.

Manufacture of Steel Cartridge Cases. (Machinery, 1944, vol. 64, Feb. 17, pp. 175–180). The coining, drawing, cleaning, heat treatment and machining operations in the mass production of 37, 40, 75 and 105-mm. steel cartridge cases at the works of the Chase Brass and Copper Company, Euclid, Ohio, are described in detail.

Cartridge Case Steel. R. E. L. Stanford. (Iron and Steel Engineer, 1944, vol. 21, Feb., pp. 31–36). Defects in steel which have been revealed in the course of manufacturing steel cartridge cases are discussed. The cause of the most serious trouble in manufacture has been traced to failure to remove all the primary pipe when cropping the ingot. The finishing temperature in the rolling is very important, and 1550–1700° F. is recommended; if not piled too hot, steel rolled at this temperature will be properly spheroidised by 48-hr. treatment at 1275° F. The best steels from the cartridge manufacturing point of view are soft, well-spheroidised steels with carbon and manganese contents close to the mean values of the contents ranges specified.

Deep Drawing Tests for Sheets. H. Esser and H. Arend. (Iron and Steel Institute, 1944, Translation Series, No. 180). An English translation is presented of a report on an investigation of the influence of blank thickness, drawing clearance and punch profile radius on the deep-drawing of sheets. The original paper appeared in Archiv für das Eisenhüttenwesen, 1940, vol. 14, Nov., pp. 223–231 (*see* Journ. I. and S.I., 1941, No. II., p. 8 A).

The Wire Drawing Die. F. C. Elder. (Mordica Memorial Lecture : Wire and Wire Products, 1944, vol. 19, Jan., pp. 23–33). The effects of changing the entry angle of wire-drawing dies on the drawing force or die pull is discussed. Tests are reported in which lengths of 0·189-in. dia. steel wire were drawn through tungsten carbide dies in a tensile testing machine carrying a strain gauge and apparatus which enabled stress-strain diagrams to be recorded. The entry angle requiring the minimum die pull when drawing soft annealed low carbon steel wire was 8°. The difference in die pull as the entry angle was reduced from 28° to 8° was only about 6%. At 45°, however, the pull was about 15% higher and at 6° about 42% higher than the minimum value at 8°.

The Effect of Back Pull when Drawing Steel Wire. W. Lueg and A. Pomp. (Iron and Steel Institute, 1944, Translation Series, No. 170). An English translation is presented of a paper which appeared in Stahl und Eisen, 1943, vol. 63, Mar. 25, pp. 229–236 (*see* Journ. I. and S.I., 1943, No. II., p. 115 A).

HEAT TREATMENT

Selecting the Heat Treatment for Gears. (Mechanical World, 1944, vol. 116, Jan. 21, pp. 65–67). Distortion during heat treatment arises from a number of causes, including the nature of the steel, the design of the part, the carburising practice, the quenching agent and the heat-treatment procedure. To reduce distortion to a minimum, the following recommendations are made : (1) Normalise or anneal before carburising ; (2) the carburising box should have a contour similar to that of the part ; (3) keep long slender parts in the vertical position ; (4) heat and cool the fewest possible times to get the required structure ; (5) choose the least drastic quenching agent to obtain the desired hardness ; and (6) employ mechanical quenching devices for parts and shapes prone to excessive metal movement in quenching.

The Production Heat Treatment of Gears. (Mechanical World, 1944, vol. 115, Feb. 4, pp. 117–120). This paper is supplementary to one on the selection of heat treatment for gears (*see* preceding abstract). The reduction of distortion is given further consideration and heat-treatment schedules are given for a 5%-nickel case-hardening steel and a 2%-nickel molybdenum steel.

The Salt Bath Heat Treatment of High Speed Steels. J. M. Pethebridge. (Australian Institute of Metals : Australasian Engineer, 1944, vol. 44, Jan. 7, pp. 22–29). An account is given of experience gained in the heat treatment of high-speed steel in salt baths heated by immersed electrodes. Thermal shock unavoidably causes cracking of the pot early in its life and some molten salt will leak through, but, as a steep temperature gradient exists in the pot walls, there is a zone not far from the interior where the temperature is below the freezing point of the salt. Once any salt leaking from the pot reaches this zone, it solidifies and seals the system against further leakage. A detailed description of the heat treatment of slab milling cutters $6\frac{1}{8}$ in. in dia., 17 in. long and $3\frac{1}{8}$ in. bore, weighing 56 lb. is given. The capital cost of the equipment for this heat treatment is high, but no other method exists whereby full hardness combined with almost perfect surface condition can be achieved.

Coil Design for Successful Induction Heating. F. W. Curtis. (Machinist, 1944, vol. 87, Mar. 18, pp. 83–86 ; Apr. 1, pp. 94–96). The principles governing the design of coils for the induction heating of metal parts for hardening and brazing are explained and many examples of coils of different shapes are described and illustrated.

Residual Stresses in Metals. W. Richmond. (Australian Institute of Metals : Australasian Engineer, 1943, vol. 43, Dec. 7, pp. 21–29). The causes and nature of residual stresses in metals

are discussed and methods of calculating longitudinal, transverse and triaxial stresses are reviewed. Stress-relieving tests at different temperatures showed that in the case of cast iron stressed at about 5 tons per sq. in. before annealing, 80% of the stress was relieved by heating to 600° C., and soaking for 6 hr. at this temperature relieved a further 17·5% of the stress. Heating to 550° C. released about 95% of the stress and the growth was only about 0·0001 in. per in. With cast steel, soaking for 12 hr. at 400° C. relieved only 20% of the residual stress, whilst soaking at 650° C. for 1 hr. reduced the initial residual stress by 97%.

Stress Relief and the Steel Casting. E. A. Rominski and H. F. Taylor. (Transactions of the American Foundrymen's Association, 1944, vol. 51, Mar., pp. 709–727). An investigation of the effect of temperature on the rate of stress relief of a 0·24% carbon cast steel carried out at the United States Naval Research Laboratory is described. The testing machine was so constructed that a very slight change in length of the specimen controlled a motor driving the loading mechanism ; in this way the 6-in. gauge length was kept constant. The specimen with its extensometer was heated in an electric furnace designed to maintain uniform heat distribution and constant temperature. With the data obtained curves were constructed by plotting the percentage relief of stress against time for annealing temperatures of 550°, 650° and 750° C., and from these curves a formula was developed with which the stress-relieving times can be determined for any steel from two or more observations on it at each of two or more temperatures.

WELDING AND CUTTING

Welding as Applied to Track Work on the L.M.S. Railway. N. W. Swinnerton and H. O'Neill. (Transactions of the Institute of Welding, 1944, vol. 7, Mar., pp. 1–14). An account is given of the methods developed by the London Midland and Scottish Railway Company for the reconditioning by welding of worn and damaged switches and crossings, for welding electric track components and for welding rails together into long lengths for running track.

Thermit Welding in Production Work. (Steel, 1944, vol. 114, Feb. 14, pp. 102–103, 134). The process of thermit welding is described with some examples of joints in stern frames and other heavy work in shipyards.

Rolling-Mill Maintenance and Production Welding Problems. T. W. Morgan. (Welding Journal, 1944, vol. 23, Jan., pp. 34–43). A description is given of the welding department which deals with both maintenance and production work at one of the rolling-mills

of the American Rolling-Mill Company. Examples of the work done by flame-cutting machines, hand torches for billet cleaning and welding repairs to mill-stand housings are described and illustrated.

The Arcos Electrode " Stabilend B." M. Roš. (Eidgenössiche Materialprüfungs- und Versuchsanstalt für Industrie, Bauwesen und Gewerbe, Zürich, Mar., 1941, Report No. 133). The results are reported of a comprehensive series of tests on the properties of welds made with the electrode " Stabilend B " which was made available in 1936 by " Arcos," La Soudure électrique autogène S.A., Lausanne-Prélaz. These tests proved that the properties of the weld metal and of the welded joint were of a higher order than those previously obtainable.

The Arcos Electrode " Ductilend 55." M. Roš. (Eidgenössische Materialprüfungs- und Versuchsanstalt für Industrie, Bauwesen und Gewerbe, Zürich, Nov., 1941, Report No. 137). The results of tests on D.C. butt-welded joints in 20-mm. thick molybdenum steel plate using the Arcos electrode " Ductilend 55 " are reported. These electrodes proved to be very suitable for welding high-quality steels of this class containing not more than $0 \cdot 20\%$ of carbon. If the carbon was in the $0 \cdot 20$–$0 \cdot 35\%$ range excellent welds were obtained, provided that the plates were preheated.

Cast Iron Rod Comes Back. A. Havens. (Machinist, 1944, vol. 87, Jan. 22, pp. 108–110). Owing to war-time restrictions on the use of bronze, cast-iron rods are now frequently used for repairing iron castings. The technique for preheating and welding large and small castings using iron filler rods is described and illustrated.

Practical Problems in the Welding of Structural Steels. M. Roš. (Swiss Acetylene Association : Eidgenössische Materialprüfungs- und Versuchsanstalt für Industrie, Bauwesen und Gewerbe, Zürich, Feb., 1941, Report No. 132). The difficulties encountered in the acetylene and electric welding of structural steel and the improved technique developed in recent years to overcome them are reviewed.

The Strength of Welded Joints and Its Calculation. M. Roš. (Eidgenössische Materialprüfungs- und Versuchungsanstalt für Industrie, Bauwesen und Gewerbe, Zürich, July, 1941, Report No. 135). The results of fatigue tests on welded joints are presented, and methods of calculating the permissible loads from fatigue strength data are explained.

Ductile Weld Metal. C. T. Gayley and J. G. Willis. (Welding Journal, 1944, vol. 23, Jan., pp. 8-S–11-S). When an electrically welded joint is made with the bead of weld metal consisting of several passes, each pass has a structure-refining heat-treatment effect on the metal of the previous pass. Weaving the arc from side to side also has this effect. If the rate of advance is too rapid while attempting to deposit very thin layers, the penetration will be poor and slag will be trapped. Tests are described, using electrodes

from $\frac{1}{8}$ in. to $\frac{5}{16}$ in. in dia., the purpose of which was to determine the welding conditions which would produce a weld of the maximum ductility. Satisfactory welds can be made with a traverse or "weaving movement" equal to six or seven times the electrode diameter; weaving at about 100 times per min. across this distance produces a weld with somewhat greater elongation and impact resistance than when traversing at 15 times per min. with the other conditions kept uniform.

The Spot-Welding Properties of Rust-Proofed Mild-Steel Sheet. W. S. Simmie and A. J. Hipperson. (Sheet Metal Industries, 1944, vol. 19, Mar., pp. 503–507). A report is presented of spot-weld tests on mild-steel strips which had been subjected to various rust-proofing processes, the objects being : (1) To determine which surfaces permitted satisfactory spot-welding; (2) to study the effect of the spot-welding process on the corrosion resistance of the surfaces ; (3) to examine the effect of each surface on the life of the electrode tips ; and (4) to determine the effect of the surface on the strength of the weld produced. The rust-proofing processes included Bonderising, Parkerising, black oxide coating with "Brunofix," browning, Sherardising, electrolytic tin and zinc coating and hot-dip galvanising. Satisfactory weldability was obtained only with those surfaces with practically no electrical resistance, i.e., Sherard-ised and tin and zinc coatings. Electrode redressing was normal in the cases of Sherardised and electro-zinc surfaces ; electro-tin necessitated redressing every 100 welds, and the galvanised surfaces every 50 welds.

The Spot Weldability of Low Carbon and other Aircraft Steels. L. C. Bibber and J. Heuschkel. (Welding Journal, 1943, vol. 22, Dec., pp. 616-S–632-S). Details are given of an investigation by the Carnegie-Illinois Steel Corporation of the spot-weldability of thin strips of plain low-carbon steels and of alloy steels for aircraft manufacture. The alloy steels included 18/8 stainless steel and low-alloy molybdenum steels. Twisting, shear, impact and tension tests of various kinds were applied after spot-welding under a wide variety of conditions. About 4000 tests were made, and the results are shown in numerous tables and graphs.

Weldability of 27% Chrome Steel Tubing. R. A. Mueller, I. H. Carlson and E. R. Seabloom. (Welding Journal, 1944, vol. 23, Jan., pp. 12-S–22-S). An investigation of the weldability of thin-walled tubes of steel containing 0·06–0·12% of carbon, 27% of chromium and 0·15% of nitrogen is reported. Austenitic steel electrodes, containing either 25% and 12% or 25% and 20% of chromium and nickel respectively, appear to be satisfactory for welding this tubing. Electrodes with 28% of chromium or 25% of chromium and 3% of molybdenum produced welds lacking in impact strength and ductility, but when the first pass was made with a 28%-chromium steel and subsequent passes with an austenitic steel, welds with satisfactory properties were obtained. Preheating

tended to broaden the heat-affected zone of the parent metal and to decrease the ductility. Stress-relieving at 1450° F. did not affect the ductility, but it lowered the impact strength.

Discussion of Means for Evaluating Weldability of Alloy Steels. S. A. Herres. (Welding Journal, 1944, vol. 23, Jan., pp. 43-S–49-S). The types of cracks which develop in welds are described and discussed. A crack would not be expected to develop parallel to the weld deposit within the zone of maximum hardness and strength except under a very unusual stress condition. Root cracks in alloy steels which are fully hardened in the heat-affected zone during the welding cycle may be prevented by heating the electrode at 600–1000° F. for a short time immediately before welding; this drives off combined and absorbed moisture and decomposes the cellulose material in the coating. Root cracks do not develop when welding with bare electrodes or with austenitic electrodes which are coated with non-hygroscopic cellulose-free materials. When beads of weld metal were deposited on alloy steel plate with bare electrodes in air and in steam atmospheres, root cracks occurred only in the steam atmosphere. This supports the theory that stresses sufficient to cause the weld-hardened structure to crack are set up by the release of hydrogen which has dissolved in the weld metal and diffused into the heat-affected zone of the parent metal during the welding cycle.

Weldability Tests of Silicon-Manganese Steels. C. E. Jackson, G. G. Luther and K. E. Fritz. (Welding Journal, 1944, vol. 23, Jan., pp. 33-S–43-S). The effect of the silicon content, with varying carbon and manganese, on the mechanical properties and weldability of steel was studied. The range of steel analysis covered by the test was carbon 0·18–0·35%, manganese 0·80–1·50% and silicon 0·65–1·20%. Silicon is almost as effective as manganese in increasing the tensile strength in the normalised condition. Silicon as a strengthener of normalised steels for welding is better than carbon or manganese, as there is less weld-hardening and higher weld ductility in silicon steels. The presence of retained austenite was observed in steel with carbon as low as 0·18% with 0·86% of manganese and 1·12% of silicon after severe quenching from 2100° F. Such steel might be dangerous in service, as tensile stresses tend to transform the austenite causing high hardness with low ductility.

Reclamation by Hard Facing. F. G. Jones. (Welding Journal, 1943, vol. 22, Oct., pp. 797–798). Numerous examples are given of the economies achieved by reclaiming parts by welding on a deposit of a corrosion-, wear- or heat-resistant alloy.

Hard-Facing in the War on Wear. J. A. Gallaher. (Welding Journal, 1944, vol. 23, Jan., pp. 16–24). The hard-facing of worn machinery parts and fittings by depositing a layer of a special alloy by welding is discussed. The properties of a number of alloys and recommendations for their application to resist abrasion, corrosion,

heat and impact are given. Many examples of hard-faced parts are described and illustrated.

Building Up High-Speed Tool Steel. E. Denz. (Zeitschift für Schweisstechnik : Welding, 1944, vol. 12, Feb., pp. 106–107, 118). Information is given on the deposition of high-speed steel on carbon steel and the repair of worn teeth on high-speed steel milling cutters by gas welding. The carbon steel tool shank is forged at the end to make a seat for the deposit ; it is brought to a red heat and the high-speed steel is welded on, using rods forged from high-speed steel scrap, as the normally made rods are un-obtainable owing to war conditions. The weld is cooled in air blast and tempered and the edge is ground to shape. For building up worn teeth the milling cutter must be heated in a closed furnace to about 400° C. before welding is commenced, and it must be stress-relieved afterwards.

Carbide Tools Tipped by Induction Brazing. P. Miller. (Machinist, 1944, vol. 87, Jan. 22, pp. 106–107). A brief illustrated description is given of the brazing of tungsten carbide tips in recesses in the shanks of tools by induction heating.

Reclamation of Perishable Tools by Low Temperature Brazing. W. A. Johnson. (Welding Journal, 1944, vol. 23, Jan., pp. 43–45). The repair of high-speed steel and other tool steels by brazing is described. The brazing is carried out with an oxy-acetylene torch and an alloy rod with a melting point not exceeding 1300° F. The brazing is done at a temperature below that which would affect the hardness of the tool.

MACHINING

The Relation Between Weldability and Wear of Cutting Tools. W. Dawihl and W. Rix. (Zeitschrift für Metallkunde : Metallurgia, 1944, vol. 29, Mar., pp. 270–272). Further experimental evidence is presented in support of the theory expressed in an earlier paper (*see* Journ. I. and S.I., 1941, No. II., p. 16 A) that the wear of cutting tools used for machining steel is due mainly to the formation of welds between the tool and the material being cut. Cubes of a carbon steel, a high-tensile alloy steel and tungsten carbide with 6 mm. sides were cut and polished. Pairs of these were welded together employing different temperatures and pressures, and the strength of the welds was determined. The welding time had little, if any, influence on the welding strength. Up to a welding pressure of 5·5 kg. per sq. mm. the strength of steel-to-steel welds increased in proportion to the pressure. Below a certain temperature (called the " sticking " temperature) it was impossible to produce a weld even under very high pressure. A tungsten carbide tool containing 15% of titanium carbide showed very little tendency to weld to

the high-tensile steel, for even at 300° C. above the sticking temperature the weld strength was less than 1 kg. per sq. mm.

Application of Tool Steels in Shop Practice. W. O. Scott. (Canadian Mining and Metallurgical Bulletin, 1943, No. 377, pp. 529–538). The properties and the selection of tool steels are discussed with special reference to methods of preparing tools in the workshop for particular purposes.

The Economical Use of High-Speed Steel. J. Farmer. (Machinery, 1944, vol. 64, Mar. 9, pp. 259–262). Changes in the composition and heat treatment of high-speed steels in the United States and Great Britain because of the shortage of tungsten are noted. Experiments in the United States have proved that an increase in the vanadium content from 1% to 2% markedly extends the cutting life of lathe and planer tools when cutting hard materials and performing finishing cuts. The function of vanadium is to give a greater red hardness, but more than 2% tends to produce " snipping," except under very good cutting conditions. Although tungsten influences the intenseness and depth of hardening, it is not so potent in these respects as either chromium or manganese.

Roll-Turning Lathe. (Iron and Steel, 1944, vol. 17, Mar., pp. 295–296). A description is given of a heavy-duty roll-turning lathe capable of dealing with rolls with collars up to 30 in. in dia. and 10 ft. long. It is driven by a 30-h.p. motor through a four-speed gear box.

CLEANING AND PICKLING OF METALS

The Use of Wetting Agents in the Degreasing of Sheet Steel. P. M. Fisk and F. F. Pollak. (Sheet Metal Industries, 1944, vol. 19, Mar., p. 427). Difficulties were experienced in the rapid degreasing of sheet metal stampings contaminated with oil consisting of 15% of saponifiable and 85% of mineral oils, and experiments were made with a number of wetting agents. The results obtained in 2 min. immersion tests at 72° C. in various solutions are reported. The solution eventually used was made up of 800 gal. of water, 6 cwt. of " Lustros " and 20 lb. of " Perminal N."

COATING OF METALS

Electro-Deposition for Engineering Purposes. A. W. Wallbank. (Engineering Inspection, 1943, vol. 8, Winter Issue, pp. 6–10). The advantages and limitations of electro-deposition for engineering purposes are reviewed, with information on the properties of chromium, nickel, copper and silver deposits.

Devices for Controlling the Distribution of Electrodeposits with Special Reference to Building-Up with Nickel or Chromium. C. J. Leadbeater. (Journal of the Electrodepositors' Society, 1944, vol. 19, pp. 35–48). Mechanical methods of contributing to the uniformity of thickness of electrolytic deposits on metal parts are reviewed and illustrated. Such devices include those integral with the part and/or the suspender, such as extension pieces, the use of current shields and " stopping-off " materials, and methods of changing the plating-bath conditions, such as altering the distance between electrodes, the use of shields and of bipolar conductors, and adapting the anode shape, size and position so as to set up equidistant current lines to the cathode.

Diffusion in Chromizing. I. R. Kramer. (Transactions of the American Institute of Mining and Metallurgical Engineers, 1944, Institute of Metals Division, vol. 156, p. 393. Information on a method of impregnating steel with chromium, or " chromising," developed in Germany by Daeves, Becker and Steinberg, is given. Gaseous chromium chloride and hydrogen are passed over the steel at 1650–1800° F. The chromium chloride reacts with the iron to form chromium and iron chloride. The chromium atoms are deposited on the surface, and diffuse in as the iron diffuses out. The principal rôle of the hydrogen is to remove the carbon from the surface of the steel. The concentration of chromium falls off gradually with increasing depth for a considerable distance down to the 13% chromium level, below which it drops steeply.

Chromizing of Steel. I. R. Kramer and R. H. Hafner. (Transactions of the American Institute of Mining and Metallurgical Engineers, 1943, vol. 154, pp. 415–422). Experiments in the chromium-impregnation of the surface of three types of steel are described. The three types comprised a plain carbon steel, a chromium-molybdenum steel and a special alloy containing 0·5% of molybdenum and 0·06% of carbon. Purified dried hydrogen was passed into a chamber filled with glass beads, where it was mixed with anhydrous hydrogen chloride. The mixture was then passed through a quartz tube containing 95% ferro-chromium, and then into the furnace containing the specimen. Data are presented on the effects of time and temperature on the case depth obtained. A high-chromium corrosion-resistant case can be produced at 1000° C. by this process in very low carbon steels and in chromium-molybdenum steels, but, with higher carbon contents, strong carbide-forming elements must be present to prevent the carbon from diffusing into the steel and forming a carbide barrier which prevents the penetration of the chromium.

A Comparison of the Properties of a Passivated and a Plain Zinc Surface. F. Taylor. (Sheet Metal Industries, 1944, vol. 19, Mar., pp. 477–483, 493). The process of passivating zinc-coated metal surfaces is described and the properties of passivated and plain zinc surfaces are compared. One treatment consists of

immersing the zinc-plated article in the passivating solution (the base is sodium or potassium dichromate acidified with sulphuric acid) for 5–15 sec. at room temperature, swilling in cold and then warm water, and drying. The zinc surface should then be covered with a khaki, iridescent or green film. The surface skin of the zinc is thus converted into a stable complex chromate film which is inert to saline and industrial atmospheres. In another process the article is immersed for 1–2 min. in a hot solution of the modified phosphate type. Numerous humidity and salt-spray test results are quoted which prove the marked superiority in the corrosion resistance of passivated over plain zinc coatings.

New Electroplating Lines Apply Tin or Zinc. (Steel, 1944, vol. 114, Feb. 7, pp. 154–156). An illustrated description is given of the continuous electrolytic plating equipment at the works of the Weirton Steel Company, where there are three lines, each 400 ft. long, which can be used for either tin or zinc plating.

Zinc Coating for Sheets by Electrolytic Process. (Iron and Steel Engineer, 1944, vol. 21, Feb., pp. 74–76). A brief description of the electrolytic plating plant at the works of the Weirton Steel Company, where strip up to 38 in. wide is now being galvanised at 160 ft. per min., is presented.

Strip Steel Electroplating with a Sodium Stannate Bath. C. E. Glock. (Electrochemical Society, Oct., 1943, Preprint No. 84-27). A description of the tinplating process at the works of the Crown Cork and Seal Company, Incorporated, Baltimore, is given. This is a continuous plant for steel strip, using a sodium stannate bath. Particular attention is paid to cleaning the strip. The pickling is carried out in a 3–5% solution of sulphuric acid which is well inhibited with rhodine and maintained at 77° C. The strip is completely immersed in the acid solution and is conveyed through it by rubber-covered rolls. It passes next through the rinsing tank, the rolls of which are kept wet by water sprays directed on them ; this is better practice than directing water sprays on the strip itself, because the latter treatment causes slight oxidation. The strip must not be exposed to the air for any length of time between the rinse and immersion in the plating solution. The plating tank contains 15,500 gal. of solution and has a row of metal contact rolls at the top and a row of insulated rolls at the bottom ; the strip passes alternately over the top and bottom rolls, and a length of 616 ft. is immersed at any one moment. There are 48 anodes in the line ; each anode is 27 in. wide and is immersed 83 in. in the solution, so that the 60,000 amp. used on the line produces an anode current density of 40 amp. per sq. ft. The cathode efficiency is 92%. The bath is made up of 80 g. per litre of sodium stannate and 10 g. per litre of sodium hydroxide and the temperature is maintained at 82–93° C.

Republic's Electrolytic Tin Plate Line Starts Production. G. R. Reiss. (Steel, 1944, vol. 114, Jan. 10, pp. 92–96). A brief de-

scription is given of the continuous electrolytic tinning plant which has recently been put in operation at the works of the Republic Steel Corporation. There are two units, each 540 ft. long, which can take strip from 16 to 38 in. wide and from 0·007 to 0·030 in. thick. About 875 ft. of strip are required to thread the two lines. Deep looping pits are provided so that the line can be continuously fed while the leading edge of one coil is welded to the trailing edge of the preceding coil.

Protective Finishes. J. S. Jones and P. M. Walker. (Journal of the Institution of Production Engineers, 1944, vol. 23, Mar., pp. 64–81). The plating of metals with tin, nickel, chromium, silver and gold is reviewed and recommendations on methods of wiring articles for immersion in the bath and on the measurement of coating thicknesses are made.

The History and Development of Phosphate Coatings with Particular Reference to the Applications of Parkerizing and Bonderizing. R. C. Davies and S. J. Scouse. (Journal of the Electrodepositors' Technical Society, 1943, vol. 19, pp. 13–22). **Development of Phosphate Coatings.** R. C. Davies and S. J. Scouse. (Metal Industry, 1944, vol. 44, Mar. 3, pp. 138–140). The development and applications of the Parkerising and Bonderising processes are discussed. The whole trend of research has been to develop solutions which, operating at reduced temperatures with less formation of sludge, give greater flexibility of operation and ease of control ; this has resulted in the use of a solution which enables iron, steel, zinc and cadmium to be treated in the same plant at the same time. For many years past, separate plants have been needed for Parkerising and Bonderising, but the " D " process has recently been developed, in which the solution will produce a coating with the characteristic properties of a Bonderised coat with an immersion time of 3–5 min., whilst if the metal is immersed for about 30 min., the coating continues to develop and acquires the properties of a Parkerised coating.

Chemical and Electrochemical Factors Influencing the Formation of Phosphate Coatings. H. A. Holden. (Journal of the Electrodepositors' Technical Society, 1944, vol. 19, pp. 23–34). The chemistry of orthophosphoric acid is considered and the development of the following three types of phosphatising solutions is reviewed : (a) Solutions consisting essentially of phosphoric acid ; (b) solutions containing metal phosphates ; and (c) solutions designed for accelerated phosphatising.

Metallurgical Department of Small Arms Ltd. W. S. Craig. (Canadian Metals and Metallurgical Industries, 1943, vol. 6, Dec., pp. 20–23). A description is given of the metallurgical operations and organisation at the works of Small Arms, Ltd., Long Branch, Ontario. Some information on the " browning " of steel is given ; this is the production of a hard black oxide coat. The consecutive stages by which this is done are : (1) Cleaning to remove grease

and oil; (2) sand-blasting; (3) coating with the browning solution by dipping, sponging or spraying; (4) heating in a dry atmosphere to 130° F.; (5) heating in a humid atmosphere to 150° F. so as to produce a red oxide coating; (6) boiling in water to convert the red oxide to black oxide; and (7) buffing to remove excess oxide. Stages (3) to (7) are repeated until four coats have been formed.

Procedures for Testing Metallizing Bond. H. Ingham and K. Wilson. (Iron Age, 1944, vol. 153, Jan. 27, pp. 44–49). Two methods are described for determining the strength of the bond of a metal-sprayed coating. One method tests the bond in shear and the other in tension.

Electrostatic Fields. G. W. Birdsall. (Steel, 1944, vol. 114, Feb. 7, pp. 128–129, 168, 169). Descriptions are given of equipment at Canadian and American plants by which blobs or " tears " of paint and other protective solutions are removed from metal articles by means of an electrode charged at a very high voltage. This type of equipment has been discussed by H. P. Ransburg (*see* Journ. I. and S.I., 1944, No. I., p. 100 A).

PROPERTIES AND TESTS

Material Quality and Safety in Constructional Engineering and the Machinery Industry. M. Roš. (Eidgenössische Material-prüfungs- und Versuchsanstalt für Industrie, Bauwesen und Gewerbe, Zürich, May, 1943, Report No. 143). A summary is presented of the data collected in the course of numerous investigations by the EMPA (*Eidgenössische Materialprüfungsanstalt*) and other institutions in Switzerland on the mechanical properties of and safety factors for brickwork, timber, cement, reinforced concrete, cast steel, cast iron, structural steel, pressure vessels, pressure pipe lines, wire ropes and the light metals.

Electrical Resistance Wire Strain Gauges. F. Aughtie. (Institution of Mechanical Engineers, Mar., 1944). Brief descriptions are given of strain gauges, developed by the National Physical Laboratory, which are based on the change in the electrical resistance of a conductor, the conductor consisting of a coil of 0·001-in. dia. wire.

Measurement of Displacement and Strain by Capacity Methods. B. C. Carter, J. F. Shannon and J. R. Forshaw. (Institution of Mechanical Engineers, Mar., 1944). Descriptions are given of capacity methods of measuring displacement and strain which have been developed at the Royal Aircraft Establishment. The instruments include multi-plate tangent type gauges, serrated condenser type gauges, torsiograph pick-up units and serrated condenser seismic-type pick-ups.

The Measurement of Strain in Components of Complicated Form by Brittle Lacquer Coatings. W. J. Clenshaw. (Institution of

Mechanical Engineers, Mar., 1944). A description is given of the application of the " Stresscoat " lacquer technique for the measurement of strain in components of complicated form. The application of the method for strain measurements in steel strip has already been described (see Journ. I. and S.I., 1944, No. I., p. 27 A).

Stresses Due to Combination of Bending and Twisting. W. A. Tuplin. (Mechanical World, 1944, vol. 115, Jan. 28, pp. 85–86). Methods of calculating the maximum stresses produced in steel shafts by the simultaneous application of a bending moment and a twisting moment are described.

Interpretation of the Notched Bar Impact Tests. P. W. Rowe. (Engineer, 1944, vol. 177, Mar. 31, pp. 247–248). The relationship between the energies expended in the two blows of the double-blow impact test on notched steel specimens was examined. For brittle material the initial blow has no effect on the remaining energy to fracture until the initial blow has reached a high value. On striking the test-piece with 90% of the mean energy necessary to cause fracture, it either broke off or else remained intact with no indication of damage. In the case of tough material, a crack could be seen after a relatively small initial blow and thereafter the extra energy required to fracture decreased approximately linearly as the initial blow increased. It is suggested that two figures be used to define a material's relative resistance to shock, namely, the total energy (E_T) required to fracture it, as usually employed, and the ratio E_C/E_T (where E_C is the energy required to increase the crack to fracture) to indicate the relative resistance to propagation of a crack.

Effect of Cold Drawing on Mechanical Properties of Welded Steel Tubing. W. E. Black. (Illinois University, 1943, Engineering Experiment Station, Bulletin Series No. 341). The results of tension, compression and hardness tests on specimens of welded 0·10% carbon steel tubing, cold-drawn from $1\frac{1}{8}$ and 1 in. outside dia. down to $\frac{5}{8}$ in. outside dia. in $\frac{1}{8}$ in. stages, are reported. Cold-drawing increased the tensile maximum and yield strengths, the compressive maximum and yield strengths and the hardness, but decreased the ductility. The increases in the tensile and compressive yield strengths were of the same magnitude for equal amounts of cold-drawing up to 50% reduction of area. This is in contrast to cold-stretching, in which the compressive yield strength is increased considerably less than the tensile yield strength. Cold-drawing up to 10% reduction of area produced relatively large increases in strength and hardness; additional cold-drawing up to 50% reduction of area caused further increases but at a slower rate. The decrease in ductility was about 70% for 10% reduction in area and about 90% for 50% reduction of area.

Determining the Internal Stresses in Steel Girders. R. V. Baud and M. Inan. (Eidgenössische Materialprüfungs- und Versuchs-anstalt für Industrie, Bauwesen und Gewerbe, Zürich, Sept., 1943,

Report No. 146). The theory of the determination of the residual stresses in wide-flange steel joists set up by non-uniform cooling of the web and flanges is explained and some photo-elastic experiments to determine the stress distribution in models are described.

Ninth Progress Report of the Joint Investigation of Fissures in Railroad Rails. H. F. Moore. (Illinois University, 1943, Engineering Experiment Station, Reprint Series No. 24). This progress report on research conducted by the Engineering Experiment Station of the Illinois University, the Association of American Railroads and the Rail Manufacturers' Technical Committee consists of the following papers which briefly report the results of tests :

Field Tests for Batter of End-Hardened Rails in Service on the Chesapeake and Ohio Railway. R. S. Jensen.

Examination of Carey End-Hardened Rails for Weeping Cracks. R. E. Cramer and N. J. Alleman. The 900 joints on the length of test track at Carey, Ohio, were tested for hardness and examined for " weeping " cracks and wear. A " weeping " crack is one at the end of the rail from which crack rust has been forced out and deposited along the edges of the crack.

Tests of Insulated Mill Cooling Containers for Rails. R. E. Cramer and N. J. Alleman. At some American steelworks where rails are rolled it is the practice to cool them in containers ; to obtain better control of the cooling it has been found necessary to insulate the containers. Time-temperature curves for rails cooled by this method are presented.

Examination of Control Cooled and Brunorized Rails which Failed in Service. R. E. Cramer.

Comparison of Drop and Bend Tests. N. J. Alleman. From a study of the elongation values obtained in drop and bend tests on rails it appears that the drop test with a spring-mounted anvil stresses a rail in a manner similar to the bend test.

First Progress Report of the Investigation of Fatigue Failures in Rail Joint Bars. Rolling-Load Tests of Joint Bars. N. J. Alleman. (Illinois University, 1943, Engineering Experiment Station, Reprint Series No. 26). The results are reported of tests on a short length of steel rail made up of two pieces joined with fish plates and four bolts. A 33-in. stroke machine applying a load of 44,400 lb. was used. The effects of bolt tension and design of rail on the rail-end damage and the number of strokes to cause fracture were investigated.

Metallurgical Control in Maintaining the Efficiency of Colliery Plant. A. Preece. (National Association of Colliery Managers : Iron and Coal Trades Review, 1944, vol. 148, Feb. 25, pp. 283–285 ; Mar. 3, pp. 329–331). Methods of reducing mechanical breakages in colliery plant are discussed under the following headings : (1) Faulty material ; (2) fatigue ; (3) failures in haulage

equipment; (4) corrosion; and (5) failures due to temperature effects.

The Effect of Quenching Temperature on the Results of the End-Quench Hardenability Test. C. E. Jackson and A. L. Christenson. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1647 : Metals Technology, 1943, vol. 10, Dec.). The results of tests are reported in which accurate determinations were made of the time taken by end-quenched specimens of different types of steel to cool through certain temperature ranges when quenched from different temperatures by the Jominy test procedure. It was established that the temperature from which the bar is quenched is important in this test, especially for steels of low hardenability, as it affects the cooling rate at distances up to about $\frac{1}{2}$ in. from the quenched end of the bar.

Ferromagnetic Testing. H. H. Jackson. (Engineering Inspection, 1943, vol. 8, Winter Issue, pp. 11–12). A brief description is given of an apparatus for rapidly determining whether the carbon content of a large number of steel tubes exceeded a certain amount. If an energised coil is placed within a secondary coil with a steel tube between them, the coupling between the coils will vary with the characteristics of the steel. In practice, two sets of coils are used ; one with a standard steel specimen, whilst the unknown is placed in the second set. The coils are connected in opposition, and the resultant voltage is applied to a detecting instrument incorporating a cathode-ray indicator. Several hundred tubes were tested in an hour by unskilled labour once the instrument was set up and calibrated.

The Possibility of Exploiting Magnetic Phenomena in the Testing of Steel. T. W. Wlodek. (Transactions of the Canadian Institute of Mining and Metallurgy, 1944, vol. 47, pp. 5–15). An investigation of the changes in the magnetic flux of steel specimens with pulsating tensile load is described. The magnetic flux was measured indirectly. The voltage and mode of variation of the e.m.f. induced in a coil surrounding the stressed steel specimen were measured as indications of the varying magnetic flux within the specimen. The pulsating tensile stresses were applied by a Schenck fatigue-testing machine. The flux increased with increasing load up to a point corresponding very closely with the yield stress. Beyond this point, slight increases in stress produced large increases in the e.m.f.

Electronic Testing Method. D. Gross. (Steel, 1943, vol. 113, Dec. 20, pp. 82–83, 127–129). A brief description is given of the Cyclograph electronic testing instrument and some of its applications. The piece of metal to be tested is inserted in a coil which is part of the instrument and also part of a tuned circuit ; the test-piece thus becomes the core of the coil and produces measurable power losses in the tuned circuit which are used to produce cathode-ray oscillograms on screens incorporated in the instrument panel.

The changes in the patterns produced on the screen as different test-pieces are inserted in the coil indicate changes in such properties as case depth, core hardness or carbon content. The instrument is particularly useful for sorting steels according to chemical analysis or heat treatment.

The Strength of Steels at High Temperatures. M. Roš and A. Eichinger. (Eidgenössische Materialprüfungs- und Versuchsanstalt für Industrie, Bauwesen und Gewerbe, Zürich, Nov., 1941, Report No. 138). The results of short-time and long-time creep tests at 400°, 450°, 500°, 550°, 600° and 700° C. on steels alloyed with (a) chromium and molybdenum, (b) chromium, nickel and tungsten, (c) chromium, nickel and titanium, (d) chromium, nickel, tungsten and vanadium, and (e) chromium, nickel, tungsten, vanadium and titanium, are reported. The effect of previous cold work on the creep properties was also investigated.

Notes on the Properties of Carbon Steels Used in Pipe Manufactured for Elevated Temperature Service. E. C. Wright. (Metal Progress, 1943, vol. 44, Dec., pp. 1127–1130). To ascertain the suitability of steels for tubes for service at high temperatures, tensile tests were made at room temperature, 400°, 500°, and 600° F. on the following steels : (1) Rimming Bessemer ; (2) rimming open-hearth ; (3) silicon-killed coarse-grained open-hearth ; (4) silicon-aluminium-killed, fine-grained, open-hearth ; and (5) silicon-aluminium-killed Bessemer. Steels (1), (2) and (3) all showed a very high increase in tensile strength at 400° F., a phenomenon often called " temper brittleness " or " blue brittleness," or " strain-ageing," whereas there was practically no increase in the case of the killed steels. Round bars tapering from 0·475 to 0·450 in. in dia. were drawn through a die 0·450 in. in dia., notched at various positions and broken in an Izod machine to obtain impact strengths related to various degrees of deformation. The killed steels exhibited a marked drop in impact value at positions of 2% or greater deformation. Fine-grained steels killed with silicon-aluminium, or with aluminium alone, are superior for tubes for service at temperatures up to 850° F.

Gas Turbines. T. Hamilton-Adams. (Iron and Steel, 1944, vol. 17, Mar., pp. 284, 294). Some alloys capable of resisting the attack of gases at 1500° C. which might be used for gas-turbine construction are discussed. One of these contains chromium 33·3%, molybdenum 30·8% and iron 35·9%.

The Mechanical Properties of Austenitic Stainless Steels. R. A. Lincoln and W. H. Mather. (Journal of Aeronautical Sciences : Sheet Metal Industries, 1944, vol. 19, Mar., pp. 435–438, 443). The properties of austenitic stainless steels are reviewed. The mechanical properties of these steels depend on the stability of the austenite. With 18% of chromium and 12% of nickel the austenite is completely stable at room temperature and the hardening produced by cold work is relatively little. As the nickel content is lowered the

stability of the austenite decreases and the rate of work-hardening increases. It was once thought that increasing the chromium made the austenite less stable, but this is not the case. A steel containing nickel 7–7·2%, chromium 17–18%, carbon 0·13–0·15% and manganese close to 0·50% in the form of cold-rolled strip and sheet can have a tensile strength of 90 tons per sq. in. with an elongation of 15%.

Improving the Physical Properties of Steel. (Steel Processing, 1944, vol. 30, Jan., pp. 33–35). The results of tensile, hardenability and low-temperature impact tests on N.E. steel 9440, treated with Grainal during manufacture in the basic open-hearth furnace, are presented. This is a low-alloy chromium-nickel-molybdenum steel.

Alternate and Ideal Steels : Medium Carbon Heat-Treated Steels. H. B. Knowlton, F. Sailer and E. H. Synder. (Metal Progress, 1943, vol. 44, Dec., pp. 1104–1111). The properties of medium carbon low-alloy steels and tests to ascertain their suitability for axles and shafts are discussed. Hardenability and tensile strength are insufficient criteria for judging a steel for these applications, and the torsional fatigue test is recommended. The results of torsional fatigue tests on a number of chromium-nickel-molybdenum N.E. steels containing about 0·45% of carbon are presented and correlated with other test results. There was no relationship between Jominy hardenability test results and the fatigue strength, neither was the penetration of hardness in a finished axle a good criterion for predicting service life.

Effects of Wartime Developments on Future Steels. W. P. Eddy, jun. (Society of Automotive Engineers : Steel, 1944, vol. 114, Feb. 14, pp. 104–108, 136–155). Metallurgical developments under wartime conditions and their probable effects are discussed. The following tendencies are noted : (1) Towards reducing the amount of alloying elements in steels ; (2) away from the deep-hardening of parts subjected to bending or torsional stresses ; (3) towards the elimination of stress raisers in the design stage ; (4) to the increased use of applied compressive stresses to surfaces ; (5) towards lower surface-finishing costs ; (6) towards reducing annealing time ; (7) the increased use of dry-cyaniding ; (8) the increased use of steel castings ; (9) a tremendous increase in the application of welding ; (10) more intelligent specification and selection of materials; (11) greater use of addition agents containing boron ; and (12) a reversion to non-ferrous metals in the post-war period.

Making Steel Specifications. H. Brearley. (Engineer, 1944, vol. 177, Feb. 18, pp. 126–128). The formulation of specifications for steel is discussed with emphasis on the idea that specifications should not be restrictive without good reason. There is reason, for example, in fixing a permissible amount of chromium in nickel steels, the point being that they should not air-harden to a troublesome extent, and there is reason why manganese should be kept below 2% in carbon steels. Hints of this kind are welcome informa-

tion to both user and maker of steel, and, whilst specifications are not to be regarded as text-books, they should not disdain to give hardly acquired and up-to-date information. The aim of specification and inspection should be to reject nothing which is as good as anything accepted of the same kind.

METALLOGRAPHY AND CONSTITUTION

High-Speed Cinematography. F. C. Johansen. (Institution of Mechanical Engineers, Mar., 1944). Brief descriptions of the Vinten, Eastman and Zeiss-Ikon high-speed cinematographic cameras are given. Pictures can be taken at speeds up to 3000 per sec. with the first two and up to 6000 per sec. with the Zeiss-Ikon camera. By projecting the pictures at slower speeds, slow-motion pictures of mechanisms affected by deflection, unbalanced forces, shock or vibration can be studied.

Preparing Small Surfaces on Specimens by Electrolytic Polishing. E. Knuth-Winterfeldt. (Jernkontorets Annaler, 1944, vol. 128, No. 2, pp. 77–80). (In Swedish). A modification of the method of A. L. De Sy and H. Haemers for the electrolytic polishing of metals is described (*see* Journ. I. and S.I., 1941, No. II., p. 29 A). This modification is for polishing very small areas of the order of 1–1·5 sq. mm. The apparatus comprises a pipette carrying a platinum cathode. The end of the pipette rests on the metal at the spot to be polished, or is held immediately above it, and a continuous stream of the electrolyte flows on to the specimen. The electrolysis time is only 10–15 sec.

Study of Internal Stress in a Metal by X-Ray Diffraction. W. A. Wood. (Institution of Mechanical Engineers, Mar., 1944). The principles of the X-ray back-reflection method of studying internal stress in metals and the methods of calculating the stress as developed at the National Physical Laboratory are explained.

Improved Methods of Printing from Radiograph Negatives. S. H. Thorpe and D. W. Davison. (Engineering, 1944, vol. 157, Mar. 31, pp. 241–242). A method is described whereby all the information existing on a radiograph negative is brought out on a single print. For this purpose use is made of a compensating filter to mask the printing light, and this enables quite high contrast to be retained for showing up defect images, while avoiding the need for reproducing a wide range of densities throughout the picture as a whole.

Realism in Metallurgical Treatment. A. C. Vivian. (Metallurgia, 1944, vol. 29, Mar., pp. 233–238). The fundamentals of the physical metallurgy of metals are explained in a manner which makes clear the effects of certain processes and heat treatments on their physical properties.

The Hardness of Metals in Relation to Atomic Structure. H. O'Neill. (Metallurgia, 1944, vol. 29, Mar., pp. 243–247). The internal conditions which determine the hardness of metallic materials are discussed. The hardness of a metal decreases with temperature, whereas its electrical resistivity rises. The ions are considered to absorb nearly all the thermal energy and the valency electrons none ; the lattice size increases and the binding force falls, so that softening is accounted for. On the other hand, the increased spacing of the ions increases the potential barriers which keep the valency electrons attached to a single atom when in the free state ; the electrons therefore become more strongly attached and the electron flow required for a current is hindered. If the elements are placed in order of atomic number in Bohr's arrangement of the Periodic Table, they show similarities in properties running in groups vertically down the table. If the reciprocal compressibilities of the metals are now plotted against their atomic numbers, the curve rises from the alkali metals on the left, passes through high values of the transitional metals and then falls as the metalloids are approached. The indentation hardness generally corresponds in periodic form with the reciprocal elastic compressibility when both are plotted against the atomic number.

CORROSION OF IRON AND STEEL

Scale Prevention by Direct Chemical Treatment of Water in Boilers. W. H. Thompson. (Iron and Steel Engineer, 1943, vol. 20, Dec., pp. 77–81). The theory and practice of the direct treatment of boiler water to prevent scale formation is discussed. Direct treatment is the treatment of the water in the boiler, not the make-up water. It usually takes the form of additions of a combination of organic and inorganic chemicals, the former to condition the sludge and make it non-adherent, and the latter to soften the water and give it the required alkalinity. Boiler tests were run in a research laboratory at 200 lb. per sq. in., the water having a total alkalinity of 25 grains per gallon (in terms of $CaCO_3$) ; the quantities of calcium and magnesium in the feed-water were varied. In a feed-water, the hardness of which was due to calcium only, a relatively large amount of scale was formed. The presence of magnesium with the calcium in the feed-water reduced the amount of scale. The presence of large amounts of magnesium hydroxide .is undesirable, however, when soluble phosphate is maintained in the boiler-water, because it adsorbs phosphate and the resulting magnesium-phosphate sludge is very sticky.

Protection by Paints Richly Pigmented with Zinc Dust. J. E. O. Mayne and U. R. Evans. (Chemistry and Industry, 1944, Mar. 18, pp. 109–110). Tests made with four different pigments—namely,

red lead, litharge, iron oxide and zinc dust—for protecting steel from attack by sea-water have shown that the best protection is obtained with zinc dust and that the maximum possible amount of dust should be incorporated in the paint.   Additional tests are now reported using the following vehicles : (1) Chlorinated rubber lacquer ; (2) polystyrene lacquer ; (3) linseed oil ; (4) medium stand-oil ; and (5) an aqueous emulsion of linseed oil.   Sufficient zinc dust was mixed with these for the dried film to contain 95% by weight of zinc.   Steel specimens were coated with these paints, a scratch-line was traced on them and they were partially immersed in sea water.   After twenty months' immersion coatings of paint (5) failed ;   one specimen with paint (1) had a brown organic growth.   In other cases no appreciable loose rust appeared.   These tests show that zinc-rich organic paints possess special value in protecting steel against sea water.   Special interest attaches to paint (2), as it can be preserved ready mixed in a closed vessel for considerable periods.

Protective Paints for Steelwork in Tropical Climates.   H. E. Whitehouse.   (Journal of the Institution of Civil Engineers, 1944, vol. 21, Feb., pp. 199–214).   The experience gained in studies made to discover a suitable paint for the Lower Zambesi bridge in Portuguese East Africa is recorded.   The following recommendations are made for the works treatment and site painting of steel to be erected in low-lying tropical areas : (1) All steelwork should be thoroughly cleaned of all rust and mill-scale and painted with a suitable primer ; this primer should be able as far as possible to resist abrasion and the normal damage due to handling and erection, and it should embody a fungicide sufficiently powerful to resist attack after drying.   (2) The subsequent coats should be adapted to the conditions which they will be called upon to resist.   (3) Different paint treatments on different parts of an important structure appear to be necessary, and very considerable economies can often be secured by this means.

It is usually possible to test normal paint treatments during the early stages of new erections, and if it is found that these break down, preliminary studies of such abnormal conditions can be made. Thorough cleaning and efficient priming will, in general, stand up satisfactorily until a suitable final treatment can be discovered.

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ORES—MINING AND TREATMENT

Mineralogical Aspects of the System $FeO-Fe_2O_3-MnO-Mn_2O_3$. B. Mason. (Stockholms Högskolas Mineralogiska Institut, Report No. 150 : Geologiska Föreningens i Stockholm Förhandlingar, 1943, vol. 65, pp. 97–180). A study has been made of the system $FeO–Fe_2O_3–MnO–Mn_2O_3$ by chemical, physical and mineralogical investigations, to determine the phase relations and in this way to define the limits of the different mineral species and to elucidate their mutual relations.

The mineral species in this system are the following : Magnetite, Fe_3O_4 ; hematite, $\alpha-Fe_2O_3$; maghemite, $\gamma-Fe_2O_3$; manganosite, MnO ; hausmannite, Mn_3O_4 ; bixbyite, $\alpha-Mn_2O_3$, with up to about 60% of Fe_2O_3 in solid solution ; jacobsite, $(Fe,Mn)_3O_4$ $(Mn_3O_4 = 16\cdot7–54\%)$; and vredenburgite, $(Mn,Fe)_3O_4$ $(Mn_3O_4 = 54–91\%)$. The literature is critically reviewed and a list of 129 references is appended.

Ore Concentration and Milling. T. B. Counselman. (Mining and Metallurgy, 1944, vol. 25, Feb., pp. 57–60). A review of developments in ore concentration plants in the United States during 1943 is presented. Heavy-media sink-and-float processes are being used for recovering iron ore from waste heaps. In processes where ferro-silicon is the medium, an increased proportion of magnetite is mixed with it to decrease the capital outlay. In the Lake Superior region the concentration of $+\frac{1}{4}$-in. material is proceeding satisfactorily and that of the $-\frac{1}{4}$-in. fraction is being investigated. A method of making ore fines into pellets in place of sintering has been demonstrated.

The Importance of Pulp Concentration and Mixing Time in Hematite Flotation. G. G. Bring. (Jernkontorets Annaler, 1944, vol. 128, No. 2, pp. 63–76). (In Swedish). Further experiments on the concentration of Swedish hematite by flotation with olein in an acid pulp after additions of waterglass and fluosilisic acid are reported, the object being to study the effect of changes in the pulp concentration and the mixing times for the waterglass, fluo-silisic acid and oleic acid. Increasing the pulp concentration and extending the mixing times increased the output of the concentrate and the iron recovery. The amount of the increase depended on the oleic acid addition and was greatest when little was present. (*See* Journ. I. and S.I., 1943, No. I., p. 116 A).

Efficient Sintering with a Dwight Lloyd Unit. M. V. Cover. (Iron Age, 1944, vol. 153, Mar. 2, pp. 46–49). Recommendations are made for the efficient working and control of a Dwight Lloyd sintering machine, 72 in. wide, with 6 boxes and capable of producing about 1000 tons of sinter per day.

Attempts to Increase Output in the Suction-Sintering of Iron Ores. H. Wittenberg and K. Meyer. (Stahl und Eisen, 1943, vol. 63, Nov. 11, pp. 817–824; Nov. 18, pp. 840–846). With the greater use of very acid ores in Germany, the output of the sintering plants has decreased considerably. Extensive investigations of the characteristics of the ores and the sintering mixture which cause this decrease, and means of effecting improvements are reported. The factors affecting the gas-permeability were analysed; the most important of these were the ability of the ores to crumble, their binding strength and the duration of the softening and melting periods. Attempts to increase output by increasing the draft and by two-layer charging were unsuccessful. Improvements were obtained by additions of lime in the form of either burnt lime or calcium hydroxide.

FUEL

Fuel and Metallurgical Furnaces. R. Whitfield. (Journal of the Institute of Fuel, 1944, vol. 17, Apr., pp. 124–128). (*See* Journ. I. and S.I., 1944, No. I., p. 182 A).

Steel Mill Boiler Units Use Supplementary Fuels. M. H. Kuhner. (Steel, 1944, vol. 114, Jan. 17, pp. 96–100, 123; Jan. 24, pp. 62–66). Factors affecting the design of boilers fired with blast-furnace gas in conjunction with other fuels are discussed. Furnaces for such boilers must be at least as large as for pulverised coal to permit time for the complete combustion of blast-furnace gas. The large proportion of non-combustible gas in blast-furnace gas necessitates intimate mixing of the gas with air to ensure complete combustion. Preheated air is desirable because the larger air volume means more thorough mixing. More uniform steam temperature from high-temperature superheaters is obtained by placing auxiliary fuel burners closer to the superheater. Gas passages and induced draft fans must be of larger size than for any other fuel.

The Importance of Preheating Air for Industrial Furnaces. L. Malm. (Teknisk Tidskrift, 1944, vol. 74, Feb. 12, pp. 161–166). (In Swedish). The application of recuperators for preheating air for furnaces in the Swedish chemical and iron and steel industries is discussed and recommendations on the design of preheaters are made.

A Theory of Similarity for Heat Exchangers. W. Traupel. (Schweizer Archiv, 1944, vol. 10, Feb., pp. 33–39). A theory of similarity for calculating rates of heat transfer when designing heat exchangers is explained.

Pitch as an Open-Hearth Fuel. J. F. Wilbur. (Iron and Steel Engineer, 1944, vol. 21, Mar., pp. 65–71). The supply and burning

of pitch for the open-hearth furnaces of the Bethlehem Steel Co., is described. This pitch comes from two coke-oven plants, in one case by insulated rail tank cars and in the other by a 4-in. pipe-line 2800 ft. long. It is stored in two insulated 13,400-gal. tanks near the open-hearth shop. The pitch is pumped from these tanks through the entire melting shop in a 4-in. line, the surplus being returned by a 3-in. line. These 3-in. and 4-in. lines with a 1-in. steam-heated line between them are lagged with 3 in. of hair felt. A pressure regulator is installed in the return line just in front of the storage tanks ; it is set to open at 120 lb. per sq. in., so that this pressure is maintained at all the furnaces. A 50-gal. heating tank is installed at each furnace ; these are controlled by the furnace operator to keep the pitch at 280–300° F. A comparison of two similar furnaces extending over five campaigns, one furnace burning only pitch and the other only oil was made. The former produced 10·68 tons of steel per hr., consuming 4,420,000 B.Th.U. per ton, and the latter 10·07 tons per hr. consuming 4,160,000 B.Th.U. per ton. The cost in refractories was approximately the same for the two types of fuel, but there was slightly more deposit in the checker chambers of the pitch-burning furnace.

Proposals for the Efficient Design, Equipment and Operation of Gas Producers, especially for Open-Hearth Furnaces when Gasifying Rhine-Westphalian Coals. Part II. G. Neumann. (Archiv für das Eisenhüttenwesen, 1943, vol. 16, Jan., pp. 237–246). Continuation of a series of articles (*see* Journ. I. and S.I., 1943, No. I., p. 151 A). The causes of explosions in gas-producer blast mains and means of preventing them are examined. A frequent cause is the sudden cessation of the demand for gas from the melting shop ; it is therefore necessary to have a reliable signalling system between the two departments. The necessity for having automatic regulators for the gas pressure and for the temperature of the steam-air mixture is discussed at length.

Proposals for the Efficient Design, Equipment and Operation of Gas Producers, especially for Open-Hearth Furnaces when Gasifying Rhine-Westphalian Coals. Part III. G. Neumann. (Archiv für das Eisenhüttenwesen, 1943, vol. 16, Feb., pp. 299–306). The author stresses the importance in gas-producer operation of having ample and accurate metering equipment, especially for the gas temperature, the temperature of the air-steam mixture, the grate temperature, the amount of blast and the gas and air pressure. The disadvantages of ordinary metering equipment are fully discussed and the need for regularly checking the accuracy of temperature measurements is pointed out. Proposals for simple meters for the blast and for the air and gas pressures are made ; these can be constructed in plant workshops and are easily maintained by the stokers. Practical hints on the operation of gas producers are given.

The Operation of High-Capacity Gas Producers. W. Blaschinz. (Stahl und Eisen, 1943, vol. 63, Nov. 18, pp. 837–840). A descrip-

tion is given of a modern gas-producing and low-temperature tar distillation plant in two units. Each unit consists of a producer 2·6 m. in dia. with a vertical shaft extending above the body; in the former there is a specially designed retort. The gas is subjected to a two-stage electrostatic continuous cleaning treatment which removes 8–10% of the volatile products as tar. The gas is cleaned sufficiently for supplying to gas engines. Operating data are presented and discussed.

Air or Gas Measurement. (Iron and Steel, 1944, vol. 17, Apr., p. 318). A description is given of the Arkon gas flow recorder for the continuous measurement of large volumes of gas at low pressures. It is therefore useful for coke-oven gas, blast-furnace gas or town gas. It is used in conjunction with an orifice plate inserted in the gas main. The flow varies with the square root of the pressure difference and the paraboloid float in the instrument is of such shape that, as it rises and falls, it automatically compensates for the square root curve, so giving a direct simple straight-line indication on the chart.

PRODUCTION OF IRON

Saving Gas by Supervision in the Operation of Blast-Furnace Stoves. K. Guthmann. (Stahl und Eisen, 1943, vol. 63, Nov. 25, pp. 860–864). Data relating to the blast temperature, to the stove temperature and to the consumption of blast-furnace gas in the stoves are presented and discussed, and it is shown how, by precise control of the timing of the change-over from one stove to another and of the stove temperature, the consumption of gas by a modern stove can be considerably reduced. A nomograph is presented which enables the stove efficiency to be read off when the operating data are available.

The Dimensions and Rating of the Blast Furnace. O. R. Rice. (Eastern States Blast Furnace and Coke Oven Association and the Blast Furnace and Coke Association of the Chicago District: Blast Furnace and Steel Plant, 1944, vol. 32, Jan., pp. 114–118; Feb., pp. 221–226). Rules and formulæ for calculating blast-furnace dimensions are discussed. The size of the hearth is related to the coke consumption by the proposed figure of 6300 lb. of coke charged per day per sq. ft. of the annular area extending 6 ft. in front of the tuyeres. The number of tuyeres is governed by spacing them at about 4 ft. circumferential distance between centres; this gives from 8 tuyeres for a 12-ft. hearth to 22 tuyeres for a 30-ft. hearth. The inside diameter of the top of a blast furnace should be such that the area is equal to the active area of the hearth, *i.e.*, the annular area

extending 6 ft. in front of the tuyeres. The greater the volume of a blast-furnace the longer it will take a given quantity of gas to travel from the tuyere level to the stock line and, within certain limits, the more efficiently will the gas react with the ore. For normal practice with a burden of Lake Superior ore the time (in sec.) the gas is retained in the furnace is equal to 185 times the furnace volume (in cu. ft.) divided by the coke consumed (in lb.) per day. Finally, the coke consumed per ton (2000 lb.) of iron can be calculated by the formula :

$$\text{Coke consumption} = \left(2 - \frac{20V}{\text{lb. of coke per day}} \right) \times 1000$$

where V is the furnace volume in cu. ft.

Thoughts on the Production of Iron. R. Durrer. (Schweizer Archiv, 1943, vol. 9, Dec., pp. 357–360). The economic aspects of reducing iron ores with electric power, with oxygen-enriched blast and with hydrogen are discussed. Under the conditions existing in Switzerland it would be possible to produce 100,000 tons of iron per annum using only 3% of the electric power produced in that country in the same period. The blast-furnace has certain inherent disadvantages, in particular, the size of the plant and the heating and blowing of large quantities of unwanted nitrogen. It is technically possible to overcome these difficulties, and it is expected that at the end of the war extensive large-scale research on revolutionary methods of making iron will be carried out.

Production Problems Face Ferro-Alloy Metallurgists. F. W. Horton. (Engineering and Mining Journal, 1944, vol. 145, Feb., pp. 103–106). War-time developments in the production in America of ferro-alloys containing boron, chromium, cobalt, manganese, molybdenum, nickel and vanadium are described.

Reduction of Ferro-Alloy Ores. G. E. Seil. (Mining and Metallurgy, 1944, vol. 25, Feb., pp. 76–77). Some developments in the production of ferro-alloys for adding manganese, silicon, chromium, nickel, molybdenum and vanadium to steel are reviewed. " Exothermic briquettes " are now being made for adding some of these elements to steel. In addition to the finely ground ferro-alloy, these briquettes contain a mixture of dry sodium nitrate and ferro-silicon. When the briquettes are put in, the heat of the bath starts a reaction between the components of this mixture, heat is liberated and the turbulence causes a thorough mixing of the alloying elements with the steel.

Production of Iron Sponge at Söderfors by the Wiberg Method. E. Améen. (Metallurgia, 1944, vol. 29, Apr., pp. 333–334). An abridged version is given of the recent report on the production of sponge iron in Sweden by the Wiberg method. (*See* p. 3 A).

Charcoal Pig Iron Project at Rusk, Texas. R. H. Sweetser. (Mining and Metallurgy, 1944, vol. 25, Mar., p. 155). The unique brown iron ores of Eastern Texas have been known and have awaited development for a long time. One million tons of the ore have been proved and allotted to the Rusk, Texas, Charcoal Pig-

Iron and Iron-Ore Project. It is planned to dismantle an idle blast-furnace and sintering plant at Pembroke, Florida, and re-erect it at Rusk. There is an abundance of hardwood at Rusk where charcoal will be made in kilns with the recovery of by-products.

Powder Metallurgy. S. V. Williams. (G.E.C. Journal, 1944, vol. 13, Feb., pp. 3–9). There are four principal methods by which metal powders are produced ; these are : (1) Milling or comminution ; (2) reducing metallic oxides ; (3) electrolytic deposition ; and (4) decomposition of gaseous compounds. Other processes include atomisation, condensation of metal vapours, shotting, granulation and mâchining. Cold pressing is the method in more general use for making parts by powder metallurgy. Shaping is not usually included in the normal sequence of operations for parts produced in large numbers, but is an economy when the number of parts does not justify a special die. Sintering is generally carried out in a reducing atmosphere such as hydrogen, cracked ammonia or partially burnt town gas. With a simple metal such as iron, the porosity after sintering decreases with increasing compacting pressure. With a fixed compacting pressure the degree of porosity varies according to the temperature, and to a less degree, the time, of sintering.

Some Aspects of Powder Metallurgy. J. C. Chaston. (Metal Treatment, 1944, vol. 21, Spring Issue, pp. 15–18, 36). Some of the papers read at the 1940 and 1941 Conferences on Powder Metallurgy held at the Massachusetts Institute of Technology are reviewed.

FOUNDRY PRACTICE

Modern Foundry Practice. C. R. Day. (Institute of Australian Foundrymen : Foundry Trade Journal, 1944, vol. 72, Apr. 13, pp. 311–318). A review is presented of developments in large foundries observed in the course of a visit in 1937 to many foundries in England, France, Germany and the United States. The survey covers moulding machines, sand treatment, core making, mould storage, melting equipment and fettling.

Trends in Iron Foundry Metallurgy. J. S. Vanick. (Metal Progress, 1944, vol. 45, Jan., pp. 83–85). Progress in the United States in the production of high-quality cast iron is reviewed, with several references to recent papers before the American Foundrymen's Association.

Duplexing in Malleable Iron Production. D. J. Reese. (Foundry, 1944, vol. 72, Jan., pp. 98, 105–106 ; Feb., pp. 122–123, 173–176). Recommendations for cupola practice in the production of malleable cast iron by the cupola/air-furnace process are made. The correct bed-coke height in inches is equal to $10 \cdot 5\sqrt{P} + 3$, where P is the

wind-box pressure in ounces. The intermediate coke charges should be about 7·5 lb. per sq. ft. of cupola cross-section and the metal charges should be about 12 times the weight of the coke charges. When the air furnace is fired with pulverised coal it consumes about 225 lb. of coal per ton of metal ; at periods of peak output this consumption may fall to 175 lb. per ton of metal.

Canadian Foundry Makes Variety of Castings. P. Dwyer. (Foundry, 1944, vol. 72, Feb., pp. 125–126, 188–190). A description is given of the plant and some of the operations at the steel foundry of the Canadian Car and Foundry Co., Montreal, where a variety of heavy castings are made, such as alloy steel rolls, manganese steel castings for mining machinery and locomotive and marine-engine castings.

Saginaw Malleable Makes Steel Castings. E. Bremer. (Foundry, 1944, vol. 72, Jan., pp. 104–105, 184, 185 ; Feb., pp. 120–121, 191, 192). A description is given of steel casting operations at the works of one of the departments of the General Motors Corporation, where about 100 tons of castings are produced per 24-hr. day. One 2-ton and two 5-ton direct arc electric furnaces are used to keep up a continuous supply of molten steel. About 565 kW. are consumed per ton of steel. Melting down and refining takes 1 hr. 40 min. in the larger furnaces. The steel is tapped into 5-ton ladles and transferred into 500-lb. ladles from which the moulds are filled. The cleaning and heat treatment of the castings are also described.

Developments in the Design and Use of Side-Blown Converter Plants. P. C. Fassotte. (Iron and Steel Institute, 1944, this Journal, Section I). A shortage of hematite iron at the time when new converter plants for steel foundries had to be erected led to a reassessment of the relative importance of the silicon and carbon reactions in the process. It was established that the carbon reaction leads essentially to the formation of carbon dioxide. The temperature increment derived from this carbon combustion is such that this reaction may be relied upon to produce the final steel temperature. Plants were therefore built in such a way that silicon could be largely dispensed with, with the concomitant elimination of hematite from the cupola charges. The operation of such a plant is discussed.

New Steel Foundry in Western Australia. (Commonwealth Engineer, 1944, vol. 31, Feb. 1, pp. 160–162). A brief illustrated description is given of a new steel foundry at the works of Tomlinson and Co., Ltd., Perth, Western Australia. The steel is produced by the cupola/converter process. As no natural foundry sands are available at Perth a synthetic mixture containing bentonite has to be prepared. Three small core ovens and one large one are provided. A well-equipped metallurgical and sand-testing laboratory has been built.

How to Change the Properties of Sand. N. J. Dunbeck. (American Foundryman, 1944, vol. 6, Jan., pp. 9–12 ; Feb., pp. 8–

12). Methods of preparing foundry sand so as to influence the strength, permeability, bond, sintering point and other properties are discussed.

Sand Control Reduces Casting Rejects. D. W. Gunther. (Foundry, 1944, vol. 72, Feb., pp. 150–152). Information is given on the effects of bonding moulding sands with one of the following materials : Kaolinite, southern bentonite, western bentonite, sea coal, pitch, resin and silica flour.

The Effect of Grain Shape on the Moulding Properties of Synthetic Moulding Sands. W. Davies and W. J. Rees. (Iron and Steel Institute, 1944, this Journal. Section I). The influence of grain shape on the behaviour of sands in synthetic moulding sand mixtures bonded with clays, core oils and core compounds has been investigated, using the recently developed method of Robertson and Émodi for the assessment of grain shape. The grain angularity is shown to vary with the source from which the sand was derived originally, the conditions under which the sand deposit accumulated and the degree of consolidation of the deposit. Typical examples of the effect of grain shape on the properties of synthetic moulding and core sand mixtures are given, and it is shown that for sands having comparable mechanical gradings the strength of mixtures prepared with angular sands is lower than that of mixtures based on rounded sands, and that the surface friability of the dried mould or core increases with the angularity of the sand. These differences are attributed to the poorer packing properties of the angular sands and to differences in the grain relationships in angular and rounded sands. The distribution of bulk density in moulds and cores is analysed, and the relationship of the bulk-density gradient to the moulding properties is discussed and illustrated. Some methods of minimising the disadvantageous effect of angularity of grain are suggested.

Precision Castings. L. L. Wyman and D. Basch. (Foundry, 1944, vol. 72, Feb., pp. 116, 203–206). A description is given of a centrifugal casting method for producing castings to very close dimensions in high-alloy steel and other alloys with high melting points. Such articles as turbine blades and milling cutters can be cast with a surface that does not require machining. It is sometimes called the " lost wax " method. (*See* Journ. I. and S.I., 1944, No. I., p. 193 A).

Continuous Casting. T. W. Lippert. (Iron Age, 1944, vol. 153, Feb. 24, pp. 48–65, 138–148). The development of the continuous casting of metals is reviewed, with descriptions of the Williams and the Goss processes for steel. The former has been the subject of an earlier paper (*see* Journ. I. and S.I., 1940, No. II., p. 10 A). In the Goss machine the mould is made up of several sections each with separate cooling. As the metal skin freezes and pulls away from the mould wall a finely divided solid material is introduced through many orifices in the wall. This material remains solid during the

casting operation and accommodates itself to the interstices between the cast metal and the mould. This protects the latter from abrasion and helps to conduct away the heat. Provision is also made for sealing off the top of the mould and introducing an inert or reducing gas above the pool of metal. Sound metal with a smooth ingot skin has been cast at a fair speed by the Goss method, but it requires further investigation and development.

Continuous Casting of Metals. The Goss Process. N. P. Goss. (American Institute of Mining and Metallurgical Engineers : Steel, 1944, vol. 114, Mar. 6, pp. 141–142, 174–178). A description is given of the Goss continuous casting process (*see* preceding abstract).

Continuous Casting of Metals. The Williams Process. E. R. Williams. (American Institute of Mining and Metallurgical Engineers : Steel, 1944, vol. 114, Mar. 6, pp. 140–141). In the Williams process of continuous casting the water-cooled vertical rectangular mould is of brass or copper up to $\frac{1}{4}$ in. in thickness. The mould is long enough to permit the solidification of only sufficient ingot skin within the mould to prevent the pressure of the molten metal within from bursting the skin as the piece emerges from the bottom of the mould. The completion of solidification is controlled by water sprayed directly against the ingot surface. Pairs of rolls below the mould compress the descending ingot and squeeze out the shrinkage cavity.

Tests Graphite Rods in Producing Cast Steel. F. J. Vosburgh and H. L. Larson. (Foundry, 1944, vol. 72, Jan., pp. 108–111, 194 ; Feb., pp. 128–129, 187, 188). Tests are reported the object of which was to study the effect of placing a carbon rod in semi-blind risers on the depth of the shrinkage cavity when making steel castings. A standard mould was prepared consisting of a single pouring gate, a runner joining two simple castings and a single vented riser between the two castings and above the runner. Steel containing 0·30% of carbon was poured at about 2890° F. in each test. Solid and hollow carbon and graphite rods $\frac{3}{8}$ in. sq. were tried ; the ends of these rested in slots in opposite sides of the circular riser cavity so that the rod was lying horizontally across the centre. When a graphite rod was used the shrinkage cavity was flat-bottomed just below the level of the lower face of the rod, whereas with carbon rods a forked cavity descending into the riser was formed. Drilling a hole down the centre of the graphite rod and thus having air present at atmospheric pressure did not affect the shape of the cavity. The shape of the rod is not important, but its size in relation to the volume of the riser must be carefully selected, as too large a rod causes excessive carbon pick-up by the steel. For best results the rod should be placed one-half of the riser diameter from the top of the riser and 2–3 in. from the centre line of the casting runner.

Shrinkage and Porosity in Light Iron Castings. C. A. Payne. (Institute of British Foundrymen : Foundry Trade Journal, 1944,

vol. 73, May 11, pp. 23–29). Factors affecting the shrinkage and porosity of iron castings are discussed. A study of the volume changes on cooling irons of different composition indicates that the most suitable composition to work to would be that of the eutectic, but in practice the solidification of such iron in varying sections results in very variable graphite structures and is therefore unsatisfactory. When castings are required in a high-duty iron, the extent to which the composition can fall below the eutectic is controlled by the desired machinability, the need for feeding or the use of denseners to overcome the differential solidification due to the wider range between liquidus and solidus.

PRODUCTION OF STEEL

Recent Developments in Steelmaking. J. Edmiston. (Metallurgia, 1944, vol. 29, Apr., pp. 304–306). Some modern steelmaking practices are described. A large plant uses a 200-ton basic-lined tilting furnace to feed an 80-ton basic-lined electric furnace. The tilting furnace is thus an active mixer; the metal in it is maintained low in carbon and phosphorus and forms an ideal basis for building up high-grade alloy melts in the electric furnace. It is comparatively easy to arrange the production of large quantities of soft low-carbon steel in basic furnaces. High rates of carbon elimination near the end of the refining stage, especially when the manganese is low, are certain to produce wild metal, and, although this can be quietened with silicon and aluminium, some finely divided silicates and alumina inclusions will remain permanently dispersed in the steel. The remedy is to strike a balance between over-oxidation and a rapid succession of heats on the one hand and more careful working with a necessary lowering of output on the other.

Increasing the Output of Open-Hearth Furnaces by Supplementary Heating of the Checker Chambers. Part I. F. Engels. (Stahl und Eisen, 1943, vol. 63, Feb. 25, pp. 145–147). In a German steelworks the capacities of three open-hearth furnaces were each increased from 38 to 62 tons, but owing to lack of space it was impossible to enlarge the checker chambers. This made it necessary to resort to carburetting with producer gas in addition to the mixed gas firing. As an alternative to the producer gas the experiment was tried of heating the checker chambers during the furnace charging by eight burners for coke-oven gas in the chamber wall above the checkerwork. Details of the results obtained with and without this supplementary heating are presented. The installation offers considerable advantages, especially in cases where the checker chambers are too

small, and it makes it possible to heat a furnace with a lean fuel gas because the high chamber temperature obtained ensures the cracking of the heavy hydrocarbons.

Increasing the Output of Open-Hearth Furnaces by Supplementary Heating of the Checker Chambers. Part II. G. Prieur. (Stahl und Eisen, 1943, vol. 63, Feb. 25, pp. 147–150). Data obtained by temperature measurements and by fuel and waste gas analyses in the course of the experiments with checker-chamber heating (*see* preceding abstract) are presented and discussed. Heating the chambers to too high a temperature had a detrimental effect on the heat transfer in the furnace by radiation from the flame ; it also increased the waste-gas loss. The advisability of installing a waste-heat boiler is considered.

New Electric Furnace Steel Making Plant Has 160,000 Tons Capacity. (Industrial Heating, 1943, vol. 10, Oct., pp. 1444–1448, 1468, 1516 ; 1944, vol. 11, Jan., pp. 70–76). A description is given of the new electric-furnace steel-making plant and practice at the works of the Carnegie-Illinois Steel Corporation, where high-quality alloy steels for war purposes are produced. The plant consists of one 35-ton and two 70-ton Héroult electric furnaces operating on 3-phase, 60-cycle A.C. They have basic-lined hearths and walls, and roofs of silica brick. Both charging and side openings are equipped with water-cooled arches and frames ; the roof rings have built-in water-cooled skew back brick support rings constructed of 18-in. channels rolled to shape and welded.

Salvaging Steel Scrap in an Electric Furnace. (Commonwealth Engineer, 1944, vol. 31, Feb. 1, pp. 157–159). A description is given of the melting practice at a works in Victoria, Australia, where a small Héroult electric furnace is used to make steel for welding electrodes from the scrap arising in washer-making. The first charge of scrap and lime amounts to two-thirds of the total charge ; power is switched on and the remainder of the charge is added in 30–40 min. The total lime amounts to 5% of the complete charge. When the carbon and manganese are low enough the first slag is raked off and replaced by a lime-fluorspar mix preparatory to refining. The finished steel contains under 0·025% each of sulphur and phosphorus.

Teeming Through Two Nozzles Simultaneously. A. Mund. (Stahl und Eisen, 1943, vol. 63, July 22, pp. 509–513). The practice of teeming, using two nozzles in the ladle simultaneously, is discussed. The layout of large and small ingot moulds in the casting pit is described. The advantages of this practice include relieving the demands on the casting-pit crane, longer life of the ladle lining and less wear on stoppers and nozzles.

Supervisory Control for Industrial Plant Power. W. A. Derr. (Iron and Steel Engineer, 1944, vol. 21, Mar., pp. 74–77). The adoption of " supervisory control " in a steelworks is described. This system provides for the remote control of electrically driven

machinery and plant in a number of different departments from a central point by relays, and it requires only one pair of low-voltage lines from the control point to each department. The relays are operated by coded impulses transmitted at the rate of about 14 per sec. The average time required to close or trip a circuit breaker is less than 3 sec.

Chain and Chain Repairs. F. W. Shaw. (Iron and Steel Engineer, 1944, vol. 21, Mar., pp. 44–46). Some points in chain manufacture and maintenance are explained. A nickel-molybdenum steel chain has been developed the strength of which after heat treatment is such that a $\frac{3}{4}$-in. chain weighing $5\frac{1}{2}$ lb. per ft. has a safe working load of 28,000 lb. It has a Brinell hardness of 250–350 ; it will stretch at least 15% before failure and has a high resistance to sudden loads.

Building Safety into a Steel Plant. H. J. Griffith. (Iron and Steel Engineer, 1944, vol. 21, Mar., pp. 40–42). The measures adopted by the Jones and Laughlin Steel Corporation to promote safety and prevent accidents at their steelworks are described.

REHEATING FURNACES

Header Manufacture. (Iron and Steel, 1944, vol. 17, Apr., pp. 345–346). Some improvements in the design of reheating furnaces and piercing and pressing operations for making headers for high-pressure water-tube boilers of high-carbon steel are described. A long furnace fired by producer gas is used through which the billets are slowly moved by a conveyor chain system. The forming of the sinuous shape of the header is done in a vertical press equipped with external dies and a spear containing other dies which are passed through the tube before pressure is applied.

Considerations and Experiences in the Construction of a Pusher-Type Furnace for Alloy Steel. K. v. d. Linden. (Iron and Steel Institute, 1944, Translation Series, No. 171). An English translation is presented of a paper which appeared in Stahl und Eisen, 1938, vol. 58, Dec. 29, pp. 1473–1480. (*See* Journ. I. and S.I., 1939, No. I., p. 216 A).

Wood-Chip and Coal-Fired Forging Furnaces with Stokers and Hot-Gas Burners. N. Ericsson. (Jernkontorets Annaler, 1944, vol. 128, No. 2, pp. 29–62). (In Swedish). A review is presented of the development in Sweden of a reliable mechanical stoker for wood chips which could also be used for coal when it is possible to revert to the latter fuel. The use of wood chips also led to the construction of a gas-producing chamber over the stoker with burner ports opening directly into the heating zone so that the gas is burnt without loss of its sensible heat. Experience gained in the operation of the new form of furnace is recorded and descriptions of

forging furnaces which were reconstructed to this form of firing are given.

FORGING, STAMPING AND DRAWING

Flow of Steel in Upsetter Forging. A. F. Macconochie. (Steel, 1944, vol. 114, Mar. 13, pp. 90–91, 132). The sequence of operations in the six-stage upset forging of shells from $2\frac{1}{2}$-in. dia. billets is described and sections of billets cut after each stage of the upsetting are illustrated to show the grain direction.

Tubular Railway Axles. (Iron and Steel, 1944, vol. 17, Apr., pp. 343–344). The method of manufacturing tubular railway wagon axles developed by the Pittsburgh Steel Co. is described. (*See* Journ. I. and S.I., 1944, No. I., p. 126 A).

Hydraulic Presses for Post-War Metal Working Production. (Steel Processing, 1944, vol. 30, Feb., pp. 90–91). Some large forging presses made by the Hydraulic Press Manufacturing Co., Ohio, and the work they can perform are described and illustrated.

Fabrication of Annealing Covers, Pressure Vessels and Galvanizing Kettles at the National Annealing Box Company. W. N. Robinson. (Steel Processing, 1944, vol. 30, Feb., pp. 83–87). The plant and processes at the works of the National Annealing Box Co., Washington, Pennsylvania, where annealing furnace covers, pressure vessels and tanks are made, are described. Heavy presses are used for forming the sheet metal and plates to the required shapes. Welding, stress-relieving and X-ray equipment are provided.

Processing Steel Parts in Blanking and Forming Dies. C. W. Hinman. (Steel Processing, 1944, vol. 30, Jan., pp. 17–20 ; Feb., pp. 96–97, 113). The stamping of blanks from strip and the design of dies for making small parts for the electrical industry are described.

Production of the M-1 Type of Helmet. (Steel Processing, 1944, vol. 30, Feb., pp. 106–108, 110). The mass production of the United States Army steel helmet is described. This is made of a non-magnetic manganese steel. The helmet is 7 in. deep and it is pressed from a flat blank in a single operation.

Forged and Coined Gears. (Steel, 1944, vol. 114, Jan. 17, pp. 78–80, 116–118). An illustrated description is given of the sequence of operations in the manufacture of differential bevel gears by forging and coining without machining. Owing to the smaller size of blank there is only 1% scrap loss, and considerable time and cost are saved as compared with former methods.

Drawbenches—Their Operation, Uses and Drives. A. L. Thurman. (Steel, 1944, vol. 114, Feb. 14, pp. 124–128, 159 ; Feb. 21, pp. 94–96, 116–122 ; Feb. 28, pp. 110–115, 130–133). Descriptions

are given of single- and double-mandrel drawbenches for drawing tubes and of the layout of the whole plant including billet furnaces, pickling and washing tanks, and storage cradles.

Drawing Galvanised Wire. (Wire Industry, 1944, vol. 11, Mar., p. 133). The difficulties encountered in drawing wire galvanised by the hot-dip process are described. With the advent of the electrolytic process of zinc coating less difficulty in drawing was experienced. With tungsten-carbide dies the highest production with minimum die wear was obtained with a die angle of 14° for sizes down to 0·048 in.; for finer sizes, and particularly in wet drawing, an angle of 12° gave the most efficient service. A reduction of 30% per draft gave best results when dry-drawing the larger sizes, whereas 20% reduction was best with the wet method. In designing the die, the junction between the bearing surface and the reducing cone should be rounded off.

ROLLING-MILL PRACTICE

Electrical Installation of the Kaiser Steel Mills at Fontana. G. Sheer. (Blast Furnace and Steel Plant, 1944, vol. 32, Jan., pp. 96–100). An illustrated description is given of the electricity transforming and distribution systems at the new steelworks at Fontana, California.

Rolling-Mill Bearings of Indigenous Wood. K. Suresch. (Stahl und Eisen, 1943, vol. 63, July 22, pp. 513–516). A rolling-mill bearing made from wood available in Germany is described, with data on its performance. The shape of the bearing is such that it can be interchanged with synthetic resin bearings. The principal wood used is that of the acacia tree.

Sealed Lubrication in Modern Sheet Mill Practice. (Sheet Metal Industries, 1944, vol. 19, Apr., pp. 629–630). A new type of sealed lubrication for the onerous conditions of sheet mill stands is described. The packing member is of oak-tanned leather for bearing temperatures up to 140° F., of chrome leather for the range 140–225° F. and of synthetic rubber for temperatures up to 300° F.

Lubrication of Non-Metallic Bearings. G. E. Reiser. (Iron and Steel Engineer, 1944, vol. 21, Mar., pp. 33–36). Experience obtained in the use of water and grease for the cooling and lubrication of synthetic-resin bearings for rolling mills is described. An easy flow of water of ample volume is more effective than a high pressure spray from jets. The water should be applied at both sides between the top and bottom half bearings. Under certain conditions of load, speed and temperature a dark film forms on the journal surface and as soon as this occurs there is a reduction in power consumption and a fall in the bearing temperature. Water-soluble oils were unsatis-

factory in maintaining this film. Extreme pressure greases containing tallow or suet are superior to other types of extreme pressure lubricants. Each type of bearing has its own characteristics, and tests are necessary to establish which is the best lubricant for it.

Roll More Tons. VII. A. E. Lendl. (Iron and Steel, 1944, vol. 17, Apr., pp. 313–318). Continuation of a series of articles. (*See* Journ. I. and S.I., 1944, No. I., p. 156 A). The calibration of rolls for flat-bottom rail sections is explained.

Jessop Steel Company Puts New 18-in. Mill on Production. C. Longenecker. (Blast Furnace and Steel Plant, 1944, vol. 32, Mar., pp. 331–333, 342). A detailed description is given of the bar mill recently put in operation at the Washington Works of the Jessop Steel Company. The mill consists of four three-high stands and one two-high finishing stand, all driven by a 1200-h.p. motor running at 327 r.p.m. The drive is through a reduction gear with a ratio of 5·9 to 1. The sizes to be produced are rounds from 3 to 6 in. in dia., squares from $2\frac{1}{2}$ to 6 in. and flats from $8 \times \frac{3}{8}$ in. to $8 \times 3\frac{1}{4}$ in.

PYROMETRY

Pyrometry at the Coke Oven. R. B. Sosman. (Transactions of the American Institute of Mining and Metallurgical Engineers, 1943, vol. 154, pp. 135–147). Investigations of the temperature variations along the face of a wall of coke as it is being pushed from an oven are described. The temperatures were taken by a Rayotube total-radiation pyrometer fixed to the coke guide car and sighted on the coke at the oven door. A current of air from a blower was provided to remove steam, smoke and dust from the path of the radiation from the coke to the Rayotube. A recording instrument with a chart travelling at 2 in. per min. was connected to the pyrometer. The difficulties in obtaining useful temperature records are discussed and their application in comparing the temperatures of different ovens in one battery and in studying the effects of changes in coke-oven operation are pointed out.

Temperature-Indicating Paints. L. C. Tyte. (Institution of Mechanical Engineers, Mar., 1944). The requirements to be satisfied by temperature-indicating pigments and the developments of such pigments are described. This development has extended to multiple transition paints. The following factors influencing the temperature-colour relationship are studied : (1) Time ; (2) liquid films and gases ; (3) heat transfer by conduction and radiation ; and (4) redistribution of temperatures during cooling of the body.

HEAT TREATMENT

Mechanised Furnaces. W. Hind. (Machine Shop Magazine, 1944, vol. 5, Apr., pp. 82–86). Descriptions are given of heat-treatment furnaces with mechanical equipment such as a pusher, conveyor or self-propelled bogie for moving the charge through the heating zone.

Continuous Cooling Transformation Diagram, from Modified End-Quench Method. C. A. Liedholm. (Metal Progress, 1944, vol. 45, Jan., pp. 94–99). A method of constructing a continuous cooling transformation diagram which can be used to predict the structure and hardness of a quenched steel is described. It is necessary to obtain cooling curves for points at different distances from the end of a Jominy end-quench specimen and then to make hardness traverses on specimens of the same steel cooled from the same temperature, but for increasing times, by the Jominy procedure before final quenching in iced brine at 32° F.

Flame Hardening Aircraft Gears. (Iron Age, 1944, vol. 153, Mar. 9, pp. 66–67). A brief account is given of the flame-hardening procedure for hardening the teeth of chromium-molybdenum steel gears for the retractable landing mechanism for aircraft.

Induction Hardening and Brazing. W. S. Craig. (Canadian Welding Society : Canadian Metals and Metallurgical Industries, 1944, vol. 7, Feb., pp. 22–24). The principles of the following commercial types of high-frequency generators are described : (1) The rotating electrical generator ; (2) the resonant spark-gap generator ; and (3) the electronic tube generator. Within reasonable limits it is possible to obtain any desired depth of hardness by induction heating without obtaining grain growth or coarsening or incomplete solution, merely by using the correct amount of power and time. The technique of induction brazing is also described.

Control Equipments for Induction Heating. F. E. Ackley. (General Electric Review, 1944, vol. 47, Mar., pp. 16–21). Descriptions are given of modern types of control equipment for core induction furnaces for brass melting and for coreless induction furnaces for heat-treating steel.

Applying Prepared Atmospheres to Metal Processing. E. G. de Coriolis. (Mechanical Engineering, 1944, vol. 66, Feb., pp. 111–114). The preparation of heat-treatment furnace atmospheres from charcoal, fuel gases, cracked gases and anhydrous ammonia and the construction of furnaces utilising these atmospheres are briefly described.

Some Effects of Sub-Zero Cooling on the Tempering of High-Speed Steel. G. A. Roberts and J. P. Gill. (Iron Age, 1944, vol. 153, Mar. 23, pp. 52–56). The effects of two forms of heat treat-

ment on the hardness of specimens of two 18/4/1 tungsten-chromium-vanadium high-speed steels are reported and discussed. In one form the specimens were heated to 1450° F., held for 5 min. at 2330° F., quenched in oil to about 800° F. and cooled in air to 70° F. In the second heat treatment the quenching was from 2330° F. to − 110° F. in a mixture of dry ice and alcohol; they were held at − 110° F. for 2 hr. Subsequent tempering was at temperatures in the 900–1100° F. range for various times. After tempering at 900° and 950° F. the samples quenched to − 110° F. were considerably superior in hardness, whilst after tempering at 1050° and 1100° F. those quenched to 70° C. had the greater hardness.

Expansion and Shrink Fits. G. W. Birdsall. (Steel, 1944, vol. 114, Feb. 28, pp. 94–98, 133–135). The preparation of refrigerating solutions and the equipment required for chilling metal parts as a preliminary to fitting one part inside another and allowing it to expand to obtain a tight fit are described.

" Pressure-Quench " Machine Minimizes Distortion of Quenched Armor Plate. C. A. Maurer. (Industrial Heating, 1944, vol. 11, Jan., pp. 28–36). A detailed description is given of a quenching machine in which armour plate from a hardening furnace is simultaneously quenched and pressed between two platens so as to prevent distortion. (See Journ. I. and S.I., 1944, No. I., p. 55 A).

The Use of Oil in the Heat Treatment of Steels. H. E. Priston. (Metal Treatment, 1944, vol. 21, Spring Issue, pp. 62–64; Iron and Coal Trades Review, 1944, vol. 148, May 12, pp. 711–712). A good quenching oil for hardening steels should have the following properties : (1) Low viscosity, because the rate of heat dissipation varies inversely as the viscosity ; (2) not too high a volatility, otherwise high evaporation losses causing thickening will occur ; (3) a sufficiently high flash point to prevent any risk of fire or excessive smoking ; and (4) a high resistance to oxidation, as this governs the rate of thickening of the oil and the degree of carbonisation. Theoretically, the higher the temperature of the oil bath the slower would be the rate of heat transfer, but in practice, the decrease in viscosity of a quenching oil due to heating more than compensates for the lowering of the rate of heat transfer owing to the higher bath temperature.

WELDING AND CUTTING

Metallic Arc Welding Electrodes. H. Lawrence. (Steel, 1944, vol. 114, Mar. 6, pp. 116–119; Mar. 13, pp. 98, 138–142). The AWS-ASTM (American Welding Society and American Society for Testing Materials) tentative specifications for iron and steel

arc-welding electrodes are explained and particulars are also given of the NEMA (National Electrical Manufacturers Association) two-colour marking plan for electrodes. The properties of welds made with AWS-ASTM E6010 electrodes are discussed.

Weldability of Steel. M. Seyt. (Metal Progress, 1944, vol. 45, Feb., pp. 298–304, 316). In the weld bead bend test as used in Germany and Switzerland to specify the weldability of a steel, a single bead is deposited down the centre of the specimen plate which is bent with the bead in tension ; the angle at which the first crack appears is thus a measure of the weldability. The maximum hardness of the heat-affected zone is, however, not clearly related to the angle determined in the above test. Weldability is therefore best measured by assessing two characteristics : (a) The maximum hardness developed just under the fusion zone ; and (b) the ability of the plate to bend, preferably after being notched with a standardised groove. Investigations relating to (a) by W. F. Hess, L. F. Merrill, E. F. Nippes, jun., and A. P. Bunk, and to (b) by G. E. Doan and R. D. Stout (see Journ. I. and S.I., 1944, No. I., pp. 56 A and 19 A, respectively) are discussed in the present paper with examples of the application of each to particular welding problems.

Steel Plate Clad with Cupro-Nickel Sheet. J. V. Kielb. (Metal Progress, 1944, vol. 45, Feb., pp. 276–279). As a substitute for the 70/30 copper-nickel alloy used for engine equipment to resist the attack of salt spray and engine exhaust gases, attempts were made to clad mild steel with 0·032-in. sheet of this alloy. Plug and spot welding the alloy sheet to the steel plate proved unsatisfactory owing to warping and air pockets between the two materials. The method finally developed was that of furnace brazing, in which the steel base plate was coated with a thin layer of flux and a sheet of copper foil was placed on this with the flux-coated copper-nickel sheet on top ; finally, steel cubes to act as weights were put on the pack which was put in the brazing furnace at a temperature of 2050° F. in an atmosphere of hydrogen.

The Deposition of Hard-Facing Alloys by Welding. P. L. Pocock. (Metallurgia, 1944, vol. 29, Apr., pp. 289–292). The oxy-acetylene welding technique for depositing stellite and other hard metal alloys on steel dies, chuck faces and valves is described.

Arc Welding of Alloy Steels. S. A. Herres. (Transactions of the American Society for Metals, 1944, vol. 33, pp. 535–563). A report is presented on the results of weld-crack sensitivity tests on low-alloy nickel-chromium steels, some containing molybdenum. A single bead was deposited in a groove down the centre of thick plates 3 in. wide. Specimens were cut transverse to the weld and bent with the weld metal in tension until a crack became visible. Cracks in the heat-affected zone of plates occur before bending only when the weld heating and cooling cycle produces a martensitic structure in the base metal immediately adjacent to the fusion

line. They are observed only when moisture- or hydrogen-bearing compounds are present in the welding atmosphere or in the electrode coating. In most cases the cracking can be prevented by either preheating the parent metal or stove-drying the electrodes.

Arc Welding Low Alloy High Tensile Structural Steel. J. G. Ball. (Welding, 1944, vol. 12, May, pp. 223–232). Data are presented on the results of hardness tests on sections of fillet welds on low-alloy steel plates as carried out in the modified form of Reeve test developed by J. Dearden and H. O'Neill (*see* Journ. I. and S.I., 1941, No. I., p. 101 A). The effect of plate thickness, preheating and type of joint on the hardness and crack-sensitivity of the heat-affected zone are evaluated and recommendations are made as to fillet dimensions and preheating temperatures for welding various thicknesses of plate.

The Arc-Welding of High-Tensile Steels. H. F. Tremlett. (Midland Metallurgical Societies : Iron and Coal Trades Review, 1944, vol. 148, Mar. 31, pp. 477–479). The essential metallurgical aspects of the welding of high-tensile steel are explained. These aspects cover plate hardenability, weld metal properties, laboratory crack tests, control of weld hardenability and crack sensitivity.

Fatigue Tests of Commercial Butt Welds in Structural Steel Plates. W. M. Wilson, W. H. Bruckner, T. H. McCrackin, jun., and H. C. Beede. (Illinois University, 1943, Engineering Experimental Station, Bulletin Series No. 344). A comprehensive series of fatigue tests was made on butt welds in $\frac{3}{4}$-in. thick carbon-steel plates by a skilled welder under expert supervision and the results were compared with those obtained on similar plates welded in various positions under varying conditions. The erratic character of the fatigue strength of butt welds in plates of this size and the limited number of specimens tested did not justify any final conclusions relating to the fatigue strength of welds made under different conditions. Specimens welded by the automatic Unionmelt and carbon-arc processes were neither significantly stronger nor significantly weaker than those welded with a manually-operated metallic arc. The abrupt change in section at the edge of the reinforcement of a butt weld is a serious stress raiser extending across the full width of the specimen, and the fatigue strength of good butt welds was markedly increased by grinding or machining the reinforcement flush with the base plate on both sides.

Fatigue Studies of Weld Test Triangular Structures with NE 8630 Steel Tubing. A. J. Williamson. (Welding Journal, 1944, vol. 23, Jan., pp. 27-S–32-S). The results are reported of fatigue tests on a welded triangular structure of 1-in. dia. steel tubing of low-alloy NE steel 8630. The structure consisted of an equilateral triangle with 18-in. sides within which was welded a second triangle joining the mid-points of the sides. Tests were made on these structures in the as-welded condition, after tempering and after normalising.

There was little difference in the fatigue strengths obtained for the three conditions.

Fatigue Tests on Arc-Welded 3% Nickel Steel. F. W. Thorne, A. Hunter and A. J. Hipperson. (Transactions of the Institute of Welding, 1944, vol. 7, Mar., pp. 38–41). The results are reported of fatigue tests on butt welds in $\frac{1}{2}$-in. 3%-nickel steel plate made with mild steel, 18/8 stainless steel and high-tensile steel electrodes. Joints made with the austenitic steel electrodes had a fatigue strength almost equal to that of the unwelded parent metal; heat treatment after welding had little effect on the fatigue strength. With mild-steel electrodes the fatigue limit was about 5 tons per sq. in. below that of the parent metal; stress relieving or hardening and tempering had very little effect in this case also.

Behavior of Welded Joints at Low Temperatures. W. Spraragen and M. A. Cordovi. (Welding Journal, 1944, vol. 23, Feb., pp. 97-S–120-S). A review of the literature to January 1, 1943, on the behaviour of welded joints in ferrous and non-ferrous metals at low temperatures is presented. The bibliography contains 82 references.

Production Spot Weld Testing. J. K. Dawson. (Welding Journal, 1944, vol. 23, Feb., pp. 108–112). A rapid method of testing spot welds in strip steel, clad steel and non-ferrous metal strip is described. Using a pair of test strips 5 in. long and 1 in. wide, 5 spot welds are made under the conditions of production, each weld being broken by a twisting motion before making the next one. Each fractured weld is then examined for excess metal splashes, incomplete fusion and slag, and the spot diameter is accurately measured. If desired a tensile test can be made on the last weld.

On the Causes of the Tendency to Fissure Formation in Welds in Steel for Aircraft. O. Werner. (Iron and Steel Institute, 1944, Translation Series, No. 174). An English translation is presented of a paper which appeared in Archiv für das Eisenhüttenwesen, 1939, vol. 12, Mar., pp. 449–455. (*See* Journ. I. and S.I., 1939, No. II., p. 96 A).

Magnetic Powder Inspection of Highly Stressed Welds, Castings and Forgings. J. A. J. Long. (Welding Journal, 1944, vol. 23, Feb., pp. 123–124). The magnetic powder process of testing welds for cracks is described. In one method two " prods " are used; these consist of bars of manganese bronze or copper, 1 in. in dia., bent at right angles 2 in. from one end. These are connected to the generator and the ends are placed 6 in. apart on the surface to be examined, the current is switched on and the magnetic powder is distributed over the area between the prods. The cracks are revealed by a heaping-up of the powder.

PROPERTIES AND TESTS

Testing of Metals and Alloys. J. W. Donaldson. (Metal Treatment, 1944, vol. 21, Spring Issue, pp. 45–51, 54). Recent American papers on the significance of the tensile test, the effect of the rate of strain on tensile test results, the relationship between stress and strain in tensile-impact tests and new methods of fatigue testing are reviewed.

Wire Tests and Specifications. G. K. Rylands. (Wire and Wire Products, 1944, vol. 19, Feb., pp. 109–113, 126–128). It is shown that the tensile test is the only one applied to wire which directly reflects a desired physical property. The measurement of elongation is of little or no value except perhaps for wire which is to be subjected to some severe manipulative process within the plastic range. Under normal conditions of use, no wire is ever subjected to torsional stresses beyond its elastic limit, so that the only information gained by the torsion test is that the wire will stand a certain number of twists, and this has little practical application, especially for mild-steel wire. The principal usefulness of the torsion test for carbon-steel wire is the indication it may give of the existence of surface defects, but for this purpose it would be better to apply a reverse torsion test consisting of five turns in one direction and five turns in the opposite direction. The wrapping test is one of general usefulness for both mild and carbon-steel wire. The almost universal works test of " snarling " is probably the best test of all, but unfortunately it cannot be described in simple terms with sufficient precision of definition.

The Stress Distribution at the Neck of a Tension Specimen. P. W. Bridgman. (Transactions of the American Society for Metals, 1944, vol. 32, pp. 553–572). A solution of the problem of determining the distribution of stress across the neck of a specimen in the tensile test is offered. This solution assumes that the contour of the specimen at the neck is a circle, and a circle is also used to approximate the lines of principal stress in the neighbourhood of the neck. This solution rigorously satisfies the conditions of plasticity in the conventional form of von Mises. The same solution also applies with an error of only a few per cent. when strain-hardening occurs to a degree found under actual conditions. The effect of the variation of tension across the section is to make the mean tension higher than the true tension of flow. Numerical values and curves are given for converting one tension to the other.

The Internal Mechanics of Cast Iron. G. Meyersberg. (Iron and Steel, 1944, vol. 17, Feb., pp. 243–247 ; Mar., pp. 289–291 ; Apr., pp. 323–328). The properties of cast iron are considered on

the assumption that it is a high-carbon high-tensile steel containing a relatively large volume of graphite. The work of A. Thum and H. Ude (*see* Journ. I. and S.I., 1930, No. I., p. 684) is reviewed at length. The influence of the graphite is defined by the " contracting factor " and the notch factor, the first defining the distribution and the second the form of development of the graphite lamellæ. They can be derived from stress-strain diagrams and the modulus of elasticity at zero load, and thus they can also be conveniently and directly determined by the Le Rolland elastometer. The notch factor, or at least a quantity from which it can be deduced, is also obtained when the elongation at fracture is known.

Plastic Flow and Rupture of Metals. C. Zener and J. H. Holloman. (American Society for Metals, Oct., 1943, Preprint No. 9). An attempt is made to co-ordinate and interpret the present knowledge of the plastic flow and rupture of metals. Two systems (that of Mohr and that of von Mises) have been in common use for specifying : (*a*) The conditions for the initiation of plastic flow ; (*b*) the precise nature of flow under a given stress pattern ; and (*c*) the relation between the strain-hardening occurring in different types of flow. These two systems are discussed in detail and a new theoretical treatment is given of their application to the problem of strain-hardening. Phenomena not previously understood are explicable in a qualitative manner by a single and precisely definable type of imperfection, namely, by the concept of microscopic cracks. These phenomena include : (1) The decrease in the rate of strain-hardening in torsion at large strains compared with the strain-hardening in tension ; (2) the elongation which accompanies large angles of twist ; and (3) the effect of prior twist upon the type of tensile fracture. A quantitative analysis, first suggested by Griffiths, is applied to these cracks, and their size is related to the microstructure.

Fatigue Strength and Notch Sensitivity in Cast Iron. R. Bertschinger and E. Piwowarsky. (Iron and Steel Institute, 1944, Translation Series, No. 182). An English translation is presented of a paper which appeared in Giesserei, 1941, vol. 28, Aug. 22, pp. 365–372 ; Sept. 5, pp. 385–389. (*See* Journ. I. and S.I., 1942, No. I., p. 241 A).

Fatigue Strength Properties of S.A.E. X4130 Tubing. G. Sachs and G. Espey. (Iron Age, 1944, vol. 153, Mar. 23, pp. 62–67). The results of fatigue tests on specimens of S.A.E. X4130 steel tubing for aircraft are reported. This is a 0·30% carbon steel with 1% of chromium and 0·20% of molybdenum. The properties of the tubing in the normalised and in the stress-relieved condition are compared. The fatigue strength, the notch-fatigue strength and the corrosion-fatigue strength were all higher in proportion to the tensile strength for the stress-relieved tubing than for the normalised tubing. Broaching the inside increased the various fatigue-strength values of thin-walled tubing, particularly in the normalised condition.

Shot Blasting Prolongs Life of Leaf, Torsion and Helical Springs.
H. H. Clark. (Steel, 1944, vol. 114, Feb. 28, pp. 100–102, 137).
Particulars are given of the equipment and procedure for shot-
blasting springs used by the Eaton Manufacturing Co., Detroit.
For most springs cast-iron shot 0·025–0·030 in. in dia. are projected
from an impeller by centrifugal force at a velocity of 200 ft. per sec.
The treatment is costly, but it prolongs the service life of the spring
by greatly improving the fatigue strength.

The Microhardness Tester as a Metallurgical Tool. Constance
B. Brodie. (American Society for Metals, Oct., 1943, Preprint
No. 7). Some applications of the diamond-pyramid microhardness
testing instrument described by C. G. Peters and F. Knoop are
discussed. (See Journ. I. and S.I., 1941, No. I., p. 65 A). Small
samples such as wire 0·20 mm. in dia. can be tested and variations
in hardness such as those occurring at grain boundaries can be
detected.

**Iron-Nickel-Aluminium-Cobalt-Copper Alloys with Preferred
Magnetic Orientation.** W. Jellinghaus. (Archiv für das Eisen-
hüttenwesen, 1943, vol. 16, Jan., pp. 247–251). A quinary iron
alloy containing 8–9% of aluminium, 23% of cobalt, 3% of copper
and 15% of nickel heat-treated in a magnetic field with subsequent
tempering is known to have preferred magnetic orientation and is
the best permanent-magnet material known. A report of an
investigation of the structure and magnetic properties of a number of
alloys of the above composition, except for the aluminium content
which varied between 5·7% and 16·7%, is presented. Specimens
from all the melts had as principal constituent one with a cubic
body-centred structure. At the lower end of the aluminium range
austenite was also present, and it was only with the highest
aluminium content that there was a cubic body-centred phase with
superstructure. The temperature-coercivity relationship showed
that the intermediate, apparently homogeneous, structure was
also of more than one phase. The explanation of the permanent
magnetism is the same as that in the case of the ternary iron-nickel-
aluminium alloys. The heat treatment in a magnetic field is only
effective within a certain range of composition which is character-
ised by homogeneous solidification, a high Curie point and the
proximity of the solubility limit of the austenite.

**The Effect of Various Alloy Additions on the Properties of
Chromium-Bearing Permanent-Magnet Steels.** H. Krainer and
F. Raidl. (Archiv für das Eisenhüttenwesen, 1943, vol. 16, Jan.,
pp. 253–260). An investigation of the effects of additions of carbon,
silicon, manganese, phosphorus, aluminium, antimony, arsenic,
copper, molybdenum, nickel, columbium, vanadium, tungsten and
tin on the magnetic properties of steels containing up to 7% of
chromium is reported. By adding two or more elements to 3·5–
4%-chromium steels and adopting a special melting technique it is
not difficult to produce an alloy having a mean value of 350,000

Gauss × Oersted. Improved chromium magnet steels can be made of the same dimensions as the tungsten steel commonly used in metering instruments, and the former can thus be substituted for the latter. Steels with about 5·5% of chromium with values for the product of the coercive force and remanence the same as that for 3·5–4%-chromium steel, but with higher coercivity, can be produced. The sensitivity of the chromium magnet steels to hot-working can be reduced by the addition of alloying elements, but some sensitivity always remains. If the magnetic properties of a chromium magnet steel are destroyed by hot-working they can be revived by a double hardening treatment.

The Creep Strength of Steel at Room Temperature. A. Krisch. (Iron and Steel Institute, 1943, Translation Series, No. 161). An English translation is presented of a report on the creep testing of two carbon steels, a chromium-molybdenum steel, a steel containing chromium 14·8% and nickel 0·22%, and an 18/8 stainless steel containing 0·20% of molybdenum. (*See* Journ. I. and S.I., 1943, No. II., p. 53 A).

Fatigue Strength and Elongation of Steels at High Temperatures. M. Hempel and H. Krug. (Iron and Steel Institute, 1944, Translation Service, No. 181). An English translation is presented of a paper which appeared in Zeitschrift des Vereines deutscher Ingenieure, 1942, vol. 86, Oct. 3, pp. 599–605.

The Development of Heat-Resisting Qualities of Cast Steel Low in Elements in Short Supply. R. Schinn and R. von Tinti. (Stahl und Eisen, 1943, vol. 63, Feb. 18, pp. 125-133; Feb. 25, pp. 151–153). An investigation of the strength properties, hot-brittleness and weldability of carbon and low-alloy cast steels at normal and at high temperatures is described. For ordinary heat-resisting applications a carbon cast steel with a tensile strength of at least 50 kg. per sq. mm. is satisfactory. Tests on the effects of the alloying elements manganese, chromium, silicon, vanadium, titanium and columbium showed that manganese and chromium increased the creep strength slightly. Silicon had only a limited effect at low temperatures. Vanadium, titanium and niobium greatly increased the creep strength. The most suitable forms of heat treatment are discussed.

The Variation of the Strength, Resistance to Oxidation and Electrical Conductivity of Metals with Temperature. D. J. McAdam, jun., and G. W. Geil. (Transactions of the American Society for Metals, 1944, vol. 33, pp. 514–534). Additional evidence is presented that the strength of metals varies linearly with temperature as measured on Kelvin's original thermodynamic scale. Diagrams derived from data in the authors' previous papers show that the logarithm of the oxidation time is linearly related to temperature expressed on the above scale. From data in the literature it is seen that the logarithm of the electrical conductivity increases nearly linearly with decreasing temperature (on the above scale) from the melting point down to the temperature of liquid air, and

sometimes to a point almost as low as the temperature of liquid hydrogen. This evidence, when considered in conjunction with the theory of interatomic forces, suggests that the strength of metals continues to increase when the temperature decreases far below that of liquid air. The temperature/electrical-conductivity relationship can be approximately represented by an equation of the same form as that for the effect of temperature on the rate of oxidation.

A Test Method for the Indirect Determination of Hydrogen in Steel. H. Kjerrman. (Jernkontorets Annaler, 1944, vol. 128, No. 1, pp. 1–12). (In Swedish). Tests were carried out to establish the relationship between the hydrogen content of steel and its elongation. The elongation was increased considerably on removing the hydrogen by holding the steel at 180° C. for 24 hr. An " elongation factor " was determined for each of several carbon steels ; this was calculated by dividing the difference between the elongations before and after degasifying by that measured after degasifying by the above treatment. There was a straight-line relationship between this factor and the hydrogen content. The tests on different types of steel revealed that : (1) Basic open-hearth steel is higher in hydrogen than acid open-hearth steel ; (2) killed basic open-hearth steel contains more hydrogen than rimming basic open-hearth steel ; (3) burning damp wood in the gas producer supplying fuel to the steel furnace causes the hydrogen content of the steel to be higher than when coal is used ; (4) a moist ladle increases the hydrogen content of the steel ; and (5) a leak in the water-cooled mechanism operating the butterfly of the reversing valve increases the hydrogen in the steel.

An Engineering Approach to the Selection, Evaluation and Specification of Metallic Materials. H. W. Gillett. (Steel, 1943, vol. 113, Nov. 22, pp. 72–77 ; Nov. 29, pp. 76–82 ; Dec. 6, pp. 110–114, 142–151 ; Dec. 13, pp. 122–129, 152–160 ; Dec. 20, pp. 88–97, 120–126 ; Dec. 27, pp. 80–88, 92 ; 1944, vol. 114, Jan. 10, pp. 98–108 ; Jan. 17, pp. 84–92 ; Jan. 24, pp. 80–90 ; Jan. 31, pp. 83–88, 102–112 ; Feb. 6, pp. 144–152, 171–175 ; Feb. 13, pp. 110–119, 156–158). A report prepared for the War Metallurgy Committee at the request of the United States War Production Board is presented. Its purpose is to assist those responsible for the selection of engineering materials by presenting information on the interpretation of test data, with special reference to the application of data relating to metals and alloys now being substituted for alloys high in elements which are in short supply.

The Effect of Small Nickel Contents on the Properties of High-Tensile Welding-Quality Chromium-Manganese-Vanadium Steel Sheets. W. Eilender, H. Arend and F. Kleinermanns. (Stahl und Eisen, 1943, vol. 63, Nov. 11, pp. 824–826). Additions of up to 0·5% of nickel were found to have no marked effect on the tensile strength, elastic limit, elongation, impact strength, weld-crack sensitivity and hardness of the zone affected by the welding heat of

chromium-manganese-vanadium steel sheets. The grain size of this steel falls in the 5–7 range on the A.S.T.M. scale. Aluminium additions did not refine the grain any further and increased the sensitivity to welding cracks.

Future Trends in High Alloy Steels. S. M. Norwood. (Metal Progress, 1944, vol. 45, Jan., pp. 86–87). It is anticipated that greater attention will be paid to the mechanical and fabricating properties of corrosion-resisting steels. An alloy containing 25% of chromium and 12% of nickel may be desirable to resist high temperatures, but the nickel may have a detrimental catalytic effect on the chemicals used in the particular process ; for such plant the nickel in the steel could be reduced considerably and its function as an austenite-former assumed by nitrogen. Austenitic steels containing about 16% of manganese have recently been introduced ; these develop excellent mechanical properties when cold-worked and can be readily fabricated by conventional methods.

Automotive Applications of National Emergency Steels. T. M. Snyder. (Steel, 1944, vol. 114, Mar. 6, pp. 128–130). The successful substitution of National Emergency steels for certain case-hardening qualities of S.A.E. steel used in automobile parts is described.

NE Steels in the Manufacture of Machine Tool Parts. G. Bissett. (Steel, 1944, vol. 114, Feb. 28, pp. 92–93, 128). Some examples are cited of the application of National Emergency steels in place of higher-alloy S.A.E. steels in the manufacture of machine tool parts.

Steel Aircraft Tubing of NE 8630 Steel. A. J. Williamson. (Metal Progress, 1944, vol. 45, Jan., pp. 115–118). The results of tensile, hardness and weldability tests on specimens cut from tubes of steel NE 8630 (containing carbon 0·30%, manganese 0·77%, nickel 0·50%, chromium 0·50% and molybdenum 0·19%) are presented.

Stainless Steels—Hot and Otherwise. H. A. Campbell. (S.A.E. Journal, 1944, vol. 52, Feb., pp. 67–72). The application of stainless steel for aero-engine exhaust systems is discussed. Stainless steel can be stabilised with either titanium or columbium, the cheaper and more easily worked titanium-stabilised steel being satisfactory for most installations ; the columbium type is used where higher yield and tensile strengths are required. The presence of boron in the flux used for welding stainless steel is detrimental and increases the cracking tendency. Zinc in contact with stainless steel at high temperatures causes rapid corrosion ; for this reason zinc-coated bolts have been replaced by cadmium-plated bolts in exhaust systems.

Preferred Aeronautical Steel Specifications. (Steel, 1944, vol. 114, Mar. 13, pp. 104–108). A revised list is presented of the aeronautical steel specifications drawn up in the United States in 1942 under the National Emergency Steel Specifications Programme with the object of increasing production through standardisation.

Carbon and Alloy Steels for War Purposes. (Metallurgia, 1944, vol. 29, Apr., pp. 310–312). Since the last review of specifications of steels for war purposes (*see* Journ. I. and S.I., 1943, No. II., p. 200 A) some new specifications in the " En " series have been issued and these are reviewed in the present paper.

METALLOGRAPHY AND CONSTITUTION

The Electron Microscope. W. Wilson. (Metal Treatment, 1944, vol. 21, Spring Issue, pp. 3–13). The principles of the electron microscope are explained and diagrams of the Finch diffraction camera and the R.C.A. (Radio Corporation of America) electron microscope are given.

Metallographic Examination. J. C. Gregory. (Sheffield Metallurgical Association : Iron and Coal Trades Review, 1944, vol. 148, Apr. 28, pp. 629–632, 636). Methods developed by the author for the macro- and micro-examination of carbon and alloy steels are described in detail.

Recent Developments in X-Ray Inspection. K. R. Van Horn. (Metal Progress, 1944, vol. 45, Jan., pp. 78–82). Some improvements in X-ray apparatus and technique for examining metals are reviewed. The introduction of 1000-kV. apparatus with new fine-grain high-contrast films has greatly reduced exposure times and improved the quality of the radiographs obtained.

Improving X-Ray Radiographs by Filtering Out Secondary Radiation. R. Taylor. (Metal Progress, 1944, vol. 45, Feb., pp. 270–272). Tests to establish means of eliminating secondary radiation from radiographs are described. An X-ray tube was set up with the focal spot 20 in. above a lead-covered table on which the film holder was placed. Midway between was fixed an $\frac{1}{8}$-in. sheet of lead with a 1·5-mm. dia. hole in it. An exposure was made with this apparatus and the results compared with those obtained when using : (*a*) A copper filter, 0·04 in. thick, near the tube ; (*b*) a Potter-Bucky grid immediately over the film holder ; (*c*) both the copper filter and the grid ; and (*d*) the copper filter and a lead foil screen, the latter in contact with the film. The combination (*c*) produced the best results, the only appreciable secondary radiation affecting the film being that from the anode face.

Radiographic Inspection. L. Mullins. (Welding, 1944, vol. 12, Mar., pp. 135–141 ; Apr., pp. 179–185). The theoretical and practical aspects of weld radiography are reviewed in a manner intended to assist both those having to decide whether the purchase of X-ray equipment is justified and workers in existing radiographic departments.

The Study of Crystal Recovery and Recrystallisation in Cold Worked Metal by Observing the Time Elapsing on Heating to Induce Changes in Hardness and Texture. A. Pomp and G. Niebch. (Zeitschrift für Metallkunde : Sheet Metal Industries, 1944, vol. 19, Mar., pp. 428–433 ; Apr., pp. 627–628). A report is presented on tests undertaken to determine to what degree crystal recovery and recrystallisation, could be identified as a primary cause of the removal by annealing of work-hardening effects in steel. This was done by ascertaining the time elapsing for changes in hardness value to occur on heating critically cold-strained soft steel at temperatures in the 620–900° C. range. According to whether crystal recovery or recrystallisation intervenes, the relaxation assumes a recognisable form which is a function of time. With crystal recovery there is a simple falling off in the relaxation without attainment of the original hardness, whilst with the onset of recrystallisation, the relaxation curve, commencing similarly, progresses to a change point and then falls sharply, and the original hardness value can be attained. With increasing temperature the recovery is so quickly transferred into recrystallisation that there is no marked change point, but the relaxation proceeds with steadily decreasing rapidity to the starting point.

Recrystallization and Twin Relationships in Silicon Ferrite. C. G. Dunn. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1691 : Metals Technology, 1944, vol. 11, Feb.). The work described is part of a programme aimed at establishing a mechanism of recrystallisation in silicon ferrite. The material used in the investigation was steel strip, 0·008 in. thick, containing 3·45% of silicon and 0·008% of carbon. The recrystallisation of plastically deformed silicon ferrite can produce complex groups of grains or particles twin-related through more than one order or generation of twins. Relationships between old and new grain orientations are considered on the basis of the first, second and third order of twins. Complicated groups of recrystallised grains are shown which are first-order twins of the separating matrix and have isolated particles of common orientation. To account for them and the origin of the entire group, some sort of secondary nucleation seems necessary. It is suggested that a grain can nucleate a twin orientation during its growth and this twin can nucleate another twin of either higher or lower order. The recovery of old grains not only inhibits growth of the nucleated grains but continues even after growth of the new grains has stopped ; such recovery can proceed far enough to create a structure very similar to that existing prior to deformation. Neumann bands within deformed grains appear to be absorbed during recovery of a grain at about 1200° C. Twins in the form of small grains or particles within a large recrystallised grain do not have stable boundaries at high temperatures.

The Carbides in the Iron-Manganese-Carbon System.   E. Öhman. (Jernkontorets Annaler, 1944, vol. 128, No. 1, pp. 13–16).   (In Swedish).   In 1936 the author completed an X-ray investigation of the carbides present in the iron-manganese-carbon system and discovered a hitherto unknown double carbide of manganese and iron which does not exist in the binary system ; it has a monoclinic crystal structure.   By solution of the carbon in the molten manganese, carbides are produced which, according to X-ray powder photographs, are isomorphous with the chromium carbides $Cr_{23}C_6$ and Cr_7C_3.   As the powder photographs are in exact agreement with those obtained for the above chromium carbides it is safe to assume that the manganese carbides have the formulæ $Mn_{23}C_6$ and Mn_7C_3.   The latter has been observed only in alloys with more than 80% of manganese, whilst $Mn_{23}C_6$ is found with up to 50% of iron and less than 6% of carbon present.   With more than 50% of iron cementite is the only carbide formed.   Both cementite and $Mn_{23}C_6$ are present even when the manganese content is up to 70%.   Manganese can replace iron in cementite to a considerable extent.

The Partition of Molybdenum in Iron-Carbon-Molybdenum Alloys at 1300 Degrees Fahr. and the Nature of the Carbides Formed.   F. E. Bowman and R. M. Parke.   (Transactions of the American Society for Metals, 1944, vol. 33, pp. 481–493).   The distribution of molybdenum in iron-carbon-molybdenum alloys of approximately eutectoid composition containing between $0\cdot26\%$ and $0\cdot98\%$ of molybdenum has been determined both for alloys prepared by transforming austenite directly and isothermally at $1300°$ F. and for alloys quenched and tempered at $1300°$ F.   Test data from the alloys prepared by these two methods support the opinion that distribution is related to hardenability.   The application of the findings to the use of steel is discussed briefly.   The identification of a face-centred cubic carbide with a lattice parameter of $10\cdot5250$ Å. and the probable formula $(Fe,Mo)_{23}C_6$ in these alloys suggests that a re-examination of existing iron-carbon-molybdenum equilibrium diagrams is required.

CORROSION OF IRON AND STEEL

Note on the Corrosion of Steel by Fertiliser.   E. G. Hallsworth. (Journal of the Society of Chemical Industry, 1944, vol. 63, Mar., pp. 95–96).   Serious damage having occurred to machinery through contact with either nitrate or chloride of potash, the corrosion of steel by these salts was investigated.   Small pieces of mild steel were polished and a few crystals of potassium nitrate were placed on some of them and crystals of potassium chloride on the others.

The specimens were then placed in desiccators containing sulphuric acid of different concentrations to give relative humidities of 25%, 30%, 50%, 65%, 80% and 90% at 95° F. The desiccators were maintained at 95° F. for two weeks. Where rusting occurred it took place within 24 hr. In cases where the crystals remained solid, no rusting took place. Potassium chloride and potassium nitrate at relative humidities of 65% and 80% respectively, can absorb sufficient moisture to allow corrosion to take place. From tests with two protective greases it appeared that machinery can be protected from corrosion by potash salts, even under tropical conditions, by heavy greasing, but the grease selected must be salt-resisting.

Behaviour of Metals in Nitric Acid. U. R. Evans. (Transactions of the Faraday Society, 1944, vol. 40, Mar.–Apr., pp. 120–130). The principal facts regarding the behaviour of metals towards nitric acid can be explained without special assumptions other than that : (1) Those equations are most probable which involve fewest molecules ; (2) oxides of type M_2O_3 are dissolved far less quickly than those of type MO, for which there is experimental evidence. The first assumption leads to the view that the attack on relatively noble metals like copper will be autocatalytic, since the two most probable equations constitute a cycle at which the concentration of nitrous acid is doubled at each stage. This in turn explains the well-known effect of stirring and of additions of urea. Autocatalysis is absent on metals like zinc which yield hydrogen-rich products. The second assumption explains why iron, although violently attacked by dilute nitric acid, is rendered passive by concentrated acid. The breakdown of passivity is connected, not with direct dissolution of the sesquioxide, but with reduction to the rapidly dissolving divalent condition ; it can be avoided by suitable anodic treatment, which prevents the destructive transformation, as is made apparent by experiments on iron covered with visible films of interference colour thickness ; such films— when out of contact with metal—resist dissolution by acid. This argument leads to an explanation of the fact that nitric acid sufficiently dilute to act violently on iron, has only a slow action on aluminium where divalent compounds are absent, or on iron containing chromium—a metal forming only unstable divalent compounds.

Mechanism of Corrosion Processes. R. M. Burns. (A.S.T.M. Bulletin, 1944, Jan., pp. 17–20). The origin and potentials of corrosion cells and the function of corrosion products in determining the end point of the process are discussed. Owing to the great speed of the primary electrode reactions and the relatively slower speed of the secondary processes of diffusion and convection, metal ions accumulate at the anode making its potential more noble, while hydrogen ions disappear at the cathode making its potential less noble. This difference in potential at the anode is

known as anode polarisation and at the cathode as cathode polarisation. These polarisations, which increase with current density, act as a counter e.m.f. which opposes the initial corrosion cell voltage. The resistance of all the common metals to corrosion in ordinary environments containing moisture can be considered in terms of anodic or cathodic polarisation, or of the two combined. The identification of the electrode controlling corrosion in a given case may be made usually by direct measurement of the potential of the metal as a whole, since this will be the composite of the potentials of the corrosion cells upon its surface. The stability of this control may be judged by the observation of the change of potential with time. Cathodic control is indicated by an electronegative position of the potential/time curve and anodic control by a noble position of this curve. An example of the practical application of potential/time curves is given.

Galvanic Corrosion. R. H. Brown. (A.S.T.M. Bulletin, 1944, Jan., pp. 21–26). The effects of polarisation and electrical resistance on the extent and intensity of the galvanic corrosion of various couples are discussed. The geometric shape and position of the metals are very important in determining the intensity and distribution of corrosive currents. Painting greatly increases the resistance of the electrical circuit of the couple. If only one metal can be painted, painting the cathode would be better than painting the anode. If the anode only is painted and the coating breaks down at local areas, then the same amount of attack could be concentrated in these areas, wereas if not painted, it might spread out over the entire area of the anode. Galvanic corrosion can sometimes serve a useful purpose; if both electrodes of a couple can be made cathodic by a current from some other source, galvanic corrosion of the couple can be prevented. The source of the current may be an inert electrode with externally applied potential, or a metal more anodic than the two metals comprising the couple. This procedure is known as " cathodic protection."

Caustic Embrittlement in Boilers. P. Hamer and E. W. Colbeck. (Chemistry and Industry, 1944, Apr. 29, pp. 163–165). Some examples of the caustic embrittlement of boilers and of vessels holding NaOH solutions are discussed. No rivet completely fills the hole it is in and it is believed that the boiler water slowly diffuses through this capillary space which leads to the ordinary atmosphere. Concentration of this slowly leaking solution takes place by evaporation and eventually solids are deposited on the atmospheric side of the leak and within the seam itself; thus the concentration varies from dilute water in the boiler to concentrated solution and solid deposit on the outside. In some critical area in between, the concentration is within limits which, combined with certain stress conditions, cause cracking to commence. Experience indicates that the " phosphate only " treatment of boiler water is not free from difficulty. The authors have not yet recorded an

instance of embrittlement in a boiler in which a $Na_2SO_4/NaOH$ ratio exceeding 2·5 has been consistently maintained in the boiler water. Small leaks in a boiler may be the warning signal indicating the onset of serious trouble. Another warning sign is the falling off of rivet heads.

The Formulation of Anti-Corrosive Compositions for Ships' Bottoms and Underwater Service on Steel. F. Fancutt and J. C. Hudson. (Iron and Steel Institute, 1944, this Journal, Section I). This paper is the first of a series in which the results of the Marine Corrosion Sub-Committee's investigations on formulated ships' bottom compositions will be reported. It deals specifically with anti-corrosive compositions; the subject of anti-fouling compositions will be discussed in later contributions relating to other work now in progress. The results of the Sub-Committee's researches to date on formulated anti-corrosive compositions lead to the following general conclusions : (1) The *pigment* should be inhibitive in character, but may with advantage be diluted with neutral pigments or extenders, provided that the proportion of inhibitor is not excessively reduced. Basic lead sulphate is a valuable pigment for this type of service, and entered into two of the best formulations in a series in which 77 different pigment combinations were incorporated in the same modified phenolic-resin medium. These two paints were pigmented, respectively, with (*a*) 8 parts of basic lead sulphate, 2 parts of aluminium and 3 parts of barytes, and (*b*) 2 parts of white lead, 4 parts of basic lead sulphate and 4 parts of Burntisland red. (2) Of the range of *media* so far tested the best have proved to be various types of phenolic- or coumarone-resin varnish and one containing chlorinated rubber. Further tests are in progress with a view to determining the best combinations of pigment and medium.

ANALYSIS

Sampling, Mixing and Grinding Techniques in the Preparation of Samples for Quantitative Analysis by X-Ray Diffraction and Spectrographic Methods. J. W. Ballard, H. I. Oshry and H. H. Schrenk. (Journal of the Optical Society of America, 1943, vol. 33, Dec., pp. 667–675). Methods developed by the United States Bureau of Mines for obtaining small representative samples and for mixing such samples intimately with an internal standard for analysis by X-ray diffraction and spectrographic methods are described.

The Application of Multiplier Photo-Tubes to Quantitative Spectrochemical Analysis. E. A. Boettner and G. P. Brewington. (Journal of the Optical Society of America, 1944, vol. 34, Jan.,

pp. 6–11). A report is presented of an investigation of the application of two electron multiplier photo-tubes for quantitative spectrochemical analysis when attached to a spectrograph. The R.C.A. 931 (Radio Corporation of America) tube is a high-vacuum phototube in which the current produced at the light-sensitive cathode is multiplied by secondary emission occurring at the nine successive dynodes within the tube.

The Use of Briquets Formed from Metal Grindings for the Spectrographic Analysis of Steel. R. E. Nusbaum, D. L. Fry and J. W. Hackett. (Journal of the Optical Society of America, 1944, vol. 34, Jan., pp. 33–40). Samples of a given alloy are often submitted for spectrographic analysis in a wide variety of shapes and sizes so that it is necessary to have a method of sampling which can be applied to all such samples. A method of preparing briquettes from samples and using them as electrodes in the arc or spark for spectrographic analysis is described. The results of manganese and silicon determinations of briquettes of cast iron and steel are given and in all cases the standard deviations in the analyses of the briquettes are comparable to those ordinarily realised for the spectrographic analyses of rods.

The Spectrographic Flat Surface Sparking Technique of Steel Analysis. C. L. Guettel. (Journal of the Optical Society of America, 1944, vol. 34, Jan., pp. 41–46). A routine method for the spectrographic analysis of steel involving a flat surface sparking technique is presented. The method has been described by F. G. Barker. (*See* Journ. I. and S.I., 1938, No. I., p. 211 P).

Accessory Equipment for Spectrochemical Analysis. J. L. Saunderson and V. J. Caldecourt. (Journal of the Optical Society of America, 1944, vol. 34, Feb., pp. 116–120). Miscellaneous accessory equipment used for spectrographic analyses in the laboratory of the Dow Chemical Company is described.

Spectrographic Analysis. Photographic Aspects of the Internal Standard Method. Part I. A. C. Coates and E. H. Amstein. (Journal of the Society of Chemical Industry, 1942, vol. 61, Feb., pp. 21–29). The method is considered in which plate calibration is carried out using metallic pencils of known composition, and the calibration curve is a log plot of concentration against the opacity ratio of the standard to impurity line. The general equation for this calibration curve is derived.

Spectrographic Analysis. Photographic Aspects of the Internal Standard Method. Part II. Theoretical Factors Governing Plate Calibration. E. H. Amstein. (Journal of the Society of Chemical Industry, 1943, vol. 62, Apr., pp. 51–58). Various methods of plate calibration are considered with special reference to the use of relative intensities. It is shown how analysed standard alloys can be eliminated from plates calibrated in terms of relative intensities, a method which also provides freedom from photographic restrictions.

Spectrographic Analysis. Photographic Aspects. Part III. Graphical Calculators Applied to Plate Calibration Using Relative Intensities. N. S. Brommelle and H. R. Clayton. (Journal of the Society of Chemical Industry, 1944, vol. 63, Mar., pp. 83–89). The application of rapid graphical calculators in quantitative spectrographic analysis is considered. The principle, construction and method of using three types of calculator are described in detail and their relative merits are discussed. An account is given of successful experience with the relative intensity method of plate calibration in routine practice.

The Use of the Spectroscope in Steelworks. J. Cameron. (Journal of the West of Scotland Iron and Steel Institute, 1943–44, vol. 51, Part II., pp. 15–27). The principles of spectrography are explained and descriptions are given of the methods and equipment used in steelworks for carrying out the following classes of analyses : (1) Analysis requiring the highest possible accuracy ; (2) analysis where a high degree of analysis must be allied with speed ; (3) analysis where a considerable amount of accuracy can be sacrificed to obtain speed ; and (4) very rapid and rough analysis as for the sorting of scrap, or for sorting mixed bars varying widely in composition.

Recommended Methods for the Determination of Silicon in Acid-Resisting High-Silicon Irons. (Journal of the Society of Chemical Industry, 1944, vol. 63, Feb., pp. 63–64). Difficulties in the determination of silicon in acid-resisting high-silicon iron led to the formation of a small sub-committee of the Ministry of Supply to investigate the position. Precautions to be observed in the analysis of this material are set out and recommended methods for umpire and routine analyses are described. A standard reference sample is in course of preparation.

A Combined Method of Chemical Analysis for Cast Iron, Malleable Iron and Steel. W. B. Sobers. (American Foundryman, 1944, vol. 6, Jan., pp. 2–5). Details are given of a procedure for making routine determinations of silicon, manganese, phosphorus, chromium, nickel and molybdenum from a single weighed sample of either plain carbon or alloy cast iron, malleable cast iron, pig-iron or steel. After evaporating the dissolved sample to dryness it is filtered to remove the silica, catching the filtrate into a volumetric flask. Aliquot parts are drawn off for the required determinations.

Electrolytic Determination of Copper in Steel and Cast Iron. W. S. Levine and H. Seaman. (Industrial and Engineering Chemistry, Analytical Edition, 1944, vol. 16, Feb., pp. 80–82). An electrolytic method of determining copper in steel and cast iron is described. A 5-g. sample is dissolved in sulphuric acid. A little ferric sulphate solution is added to the solution and the residue ; this oxidises the undissolved copper in the residue to divalent copper. Electrolysis of the solution is carried out using a platinum gauze cathode ; the anode is a platinum wire in an alundum thimble

filled with 4% sulphuric acid. The electrolysis takes about 45 min.

Electro-Chemical Methods of Analysis. G. Jessop. (Sheffield Metallurgical Association : Iron and Coal Trades Review, 1944, vol. 148, Apr. 28, pp. 641–643). Examples are given of the use of potentiometric titration apparatus and of the polarograph in electro-chemical methods of analysing solutions of metal samples.

General Methods of Micro-Chemical Analysis of Metals. I. H. Hadfield. (Metal Treatment, 1944, vol. 21, Spring Issue, pp. 19–28). Gravimetric and volumetric methods of making micro-chemical analyses of metals are reviewed.

Preparation of Coke Samples. J. H. Jones. (Fuel in Science and Practice, 1944, vol. 23, Mar.–Apr., pp. 40–41). It has been observed in coke-oven tests that the phosphorus content of the coke samples determined in the laboratory was higher than that calculated from the coke yield and the phosphorus content of the coal. The cause of this discrepancy has been found by careful tests to be contamination of the coke samples by erosion of the iron of the mills employed in preparing the samples. High-phosphorus iron should never be employed for grinding metallurgical coke.

The Rapid Determination of Moisture and Ash in Coal and Coke. R. Belcher and C. E. Spooner. (Fuel in Science and Practice, 1944, vol. 23, Mar.–Apr., pp. 46–49). Two methods are described for the rapid determination of moisture in air-dried coal and one for the rapid determination of ash ; the two determinations can be carried out simultaneously by the same operator in 20 to 25 min.

The Preparation of Coal as Received for Rapid Analysis. R. A. Mott and C. E. Spooner. (Fuel in Science and Practice, 1944, vol. 23, Mar.–Apr., pp. 42–45). The methods of determining moisture and ash in coal described by Belcher and Spooner (*see* preceding abstract) require that the coal is crushed to pass a British Standard 72-mesh sieve, and it is not possible to crush the coal rapidly to this size if it is visibly wet. It is shown that surface moisture can be flashed off coals crushed to pass $\frac{1}{2}$-in. and $\frac{1}{8}$-in. sieves at the rate of 1% per min. by using a thin layer of coal in an oven at 200° C. Suitable grinding equipment for a variety of conditions is described.

The Use of the Discriminant Function in the Comparison of Proximate Coal Analyses. W. D. Baten and C. C. DeWitt. (Industrial and Engineering Chemistry, Analytical Edition, 1944, vol. 16, Jan., pp. 32–34). Statistical methods are described for comparing the proximate analyses and B.Th.U. determinations of coal from two mines ; these make use of the discriminant function developed by Fisher.

Precision of the Volatile-Matter Determination for Anthracite. Low-Temperature Coke and Subbituminous Coal. W. A. Selvig. (United States Bureau of Mines, Dec., 1943, Report of Investigations No. 3739). A statistical analysis is made on duplicate determinations

of volatile matter of 100 samples each of anthracite, low-temperature coke and sub-bituminous coal made by A.S.T.M. standard methods. From the results it is concluded that the A.S.T.M. permissible differences between duplicate determinations of volatile matter by the same laboratory on the same sample should be increased to permit 0·3% for anthracite, 0·5% for low-temperature coke and 0·7% for sub-bituminous coal.

BOOK NOTICES

Special and Alloy Steel Committee. "*A Metallurgical Study of German and Italian Aircraft Engine and Airframe Parts.*" By the Aero Component Sub-Committee of the Technical Advisory Committee to the Special and Alloy Steel Committee. Arranged in co-operation with the Committee by C. A. Otto. 8vo. Pp. 140. Illustrated. Manchester, 1943 : The Kennedy Press, Ltd. (Price 10*s*. 6*d*.)

This report constitutes a summary of data resulting from the metallurgical examination of German and Italian aircraft engine and airframe parts by the Aero Component Sub-Committee of the Technical Advisory Committee of the Special and Alloy Steel Committee formed for this purpose. This Sub-Committee, of which the late Dr. W. H. Hatfield, F.R.S., was chairman, comprised the late Mr. W. H. Dyson, of the Ministry of Aircraft Production; Dr. H. Sutton, Royal Aircraft Establishment; Dr. R. Genders, Superintendent, Technical Applications Metals, Ministry of Supply; Mr. H. Bull, Messrs. Brown Bayley's Steelworks Ltd.; Mr. H. H. Burton, the English Steel Corporation Ltd.; Mr. W. J. Dawson, Messrs. Hadfields Ltd.; Mr. D. A. Oliver, Messrs. Wm. Jessop and Sons Ltd.; Dr. T. Swinden, The United Steel Companies Ltd.; and the late Mr. G. Stanfield, Secretary, Brown-Firth Research Laboratories. The parts examined represent an extensive range of the various types of enemy aircraft which have fallen into the hands of the R.A.F. since the beginning of the war. The principal object of these investigations was to obtain data on the types and quality of materials used, methods of manufacture, efficiency of the heat treatment to which the parts had been submitted, together with any other information which might prove of value, as, for example, details of the finish. Further, the influence of restrictions due to our blockade on enemy procedure and selection of materials was kept in mind. Attention was given chiefly to engine parts, but a number of airframe and miscellaneous components were included. Special features concerning design had been noted in certain instances, but these were not the primary object of the investigations. For the purpose of this report components of the same type from different aircraft have been considered together and the main features summarised. For fuller details the individual reports should be consulted. The book includes a brief description of the enemy aircraft examined and deals with such components as crankshafts, connecting rods, gudgeon pins and wrist pins, cylinders and cylinder liners, inlet and exhaust valves, valve springs, gears, bearings, camshafts and airscrew shafts, castings and other miscellaneous engine parts. The work included in this report embraces the results of investigations

carried out from the beginning of the war until towards the end of 1941, but investigations have continued and are still in progress, and the work is being carried out meticulously. Naturally, no comparisons are made in the report with corresponding parts in British and American aircraft, neither are certain aspects, which the investigations have shown to be open to criticism, emphasised. All the proceeds from the sales of this book are to be placed to the account of the Royal Air Force Benevolent Fund; an acknowledgment in the form of a letter from Lord Riverdale, Chairman of the Appeals Committee of this Fund, is contained in each copy. Those requiring copies are advised to make application to the publishers direct.

STREET, A., and W. ALEXANDER. "*Metals in the Service of Man.*" (Pelican Books.) 8vo. Pp. 192. Illustrated. Harmondsworth, Middlesex, 1944 : Penguin Books. (Price 9*d.*)

There has long been need for a work dealing with the broad field of metallurgy that would interest the student or general reader rather than bewilder him. In the compilation of this book the authors have accomplished a somewhat difficult task, and have successfully made available to those of little or no scientific training a well-illustrated and understandable introduction to the mysteries of the science of metals. Care has been taken to avoid the use of too many technical terms, but where such terms have been introduced they are defined in a glossary at the end of the book. In these days of high prices it is of great advantage to the student to be able to acquire such a useful work for the outlay of a few pence. The book contains the following chapters : I. Metals and Civilisation; II. How We Get Our Metals; III. Making Iron; IV. Making Aluminium; V. Alloys; VI. Metals under the Microscope; VII. The Inner Structure of Metals; VIII. The Shaping of Metals; IX. The Testing of Metals; X. Corrosion; XI. The Metallurgy of Iron and Steel; XII. The Rôle of Carbon in Steel; XIII. Cast Iron and Alloy Steels; XIV. Aluminium and Its Alloys; XV. Magnesium and Its Alloys; XVI. Copper and Its Alloys; XVII. Four Common Metals; XVIII. Some Minor Metals; XIX. The Joining of Metals; XX. Powder Metallurgy; XXI. Metals in War Time; XXII. The Future of Metals.

UNITED STATES STEEL CORPORATION. "*Atlas of Isothermal Transformation Diagrams.*" 4to. Pp. 103. Pittsburgh, 1943.

This Atlas contains the isothermal transformation diagrams, in a standard form and size, for 47 different steels as determined at the Research Laboratory, United States Steel Corporation at Delaware, New Jersey.

The Atlas opens with a table of contents giving the compositions of the steels the transformation diagrams of which follow; this also serves as an index. Some five thousand words are then devoted to a consideration of the significance of the isothermal transformation diagram of a steel and to the explanation of a typical diagram. This is followed by a selected bibliography with thirty-four references.

The actual diagrams are classified under seven different sections, namely, carbon and carbon-manganese steels, nickel steels, chromium steels, molybdenum steels, silicon steels, standard steels with more than one principal alloying element, and a final section devoted to special comparisons. Each diagram is printed on a sheet of thick paper, approximately 9×10 in. The scales are remarkably open and are clearly and boldly defined.

Each chart includes sufficient information to identify the steel with respect to chemical composition, the austenitising temperature

employed and the austenite grain size established at that temperature. The temperature scale both in Fahrenheit and Centigrade appears in the left-hand margin and time is plotted on a logarithmic scale along the horizontal axis at the bottom of the chart. For convenience in quickly locating some familiar reference point on the time scale, a few representative time intervals are shown in terms of minutes, hours or days. In the right-hand margin is shown the Rockwell C hardness of the product of complete isothermal transformation at the different temperature levels investigated.

On each chart there are three curves. The boldly drawn curves on the left and the right represent the time for the commencement and for the completion of the austenite change respectively. The dotted curve located between these two curves represents, for each temperature level, the time at which half of the total austenite has transformed.

The United States Steel Corporation are to be congratulated on producing such an excellent work and the diagrams cannot fail to be of the greatest possible value to anyone associated with the heat treatment of steel, particularly aircraft steel. The publication is in every way of first-class quality, the reproduction of the diagrams is excellent and the general make-up leaves nothing to be desired.

J. FERDINAND KAYSER.

REFRACTORY MATERIALS

The Selection of Blast-Furnace Refractories. H. M. Kraner. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1727 : Metals Technology, 1944, vol. 11, Apr.). The testing of refractory bricks for blast-furnace linings is discussed and the results are presented of tests in which the amount of carbon deposited in bricks by heating them in a carbon-monoxide atmosphere was determined. Refiring the bricks does not prevent the deposition of carbon, but it increases the mechanical strength, lowers the permeability and reduces the tendency to disintegrate in atmospheres containing carbon monoxide.

Industrial Survey of Refractory Service Conditions in Electric Steel Furnaces. Part I. Arc Furnaces. E. E. Callinan. (American Society for Testing Materials : Industrial Heating, 1944, vol. 11, Jan., pp. 112–120). The linings of both acid and basic electric arc furnaces are considered. The position of the electrodes with respect to the furnace side walls affects the life of the refractories. The wall and banks nearest to the mast holding the electrodes is the hottest part of the furnace, and it is here that the greatest erosion takes place. Graphite electrodes are more expensive and more fragile than amorphous carbon electrodes, and the higher thermal conductivity of the former kind causes a greater loss of heat towards the exposed end.

Direct-Arc Electric Furnace Refractories. E. K. Pryor. (Transactions of the American Foundrymen's Association, 1944, vol. 51, June, pp. 878–894). The properties of refractories and their relation to direct-arc furnace operating conditions are discussed. The construction of brick roofs and of brick and monolithic furnace linings is described in detail, with notes on the causes of roof failures.

FUEL

Steam in Steelworks.—II. G. Graham. (Iron and Steel, 1944, vol. 17, May, pp. 353–359). Continuation of a series of articles (*see* p. 1 A). The caulking of cracks in boiler settings and the insulation method of preventing cold air from being drawn through the brickwork are described. The choice of steam valves and their maintenance are discussed.

" Sinuflo " Waste-Heat Boilers. (Engineering, 1944, vol. 157, June 9, p. 456). Two " Sinuflo " waste-heat boilers, one operating in conjunction with soaking pits and the other on the waste gas from a 250-ton open-hearth furnace are described. These boilers consist of cylindrical shells having " Sinuflo " tubes extending between the end plates and occupying roughly two-thirds of the area of the plates.

The Use of Steel Recuperators in Iron and Steel Works. J. Müller-Berghaus. (Iron and Steel Institute, 1944, Translation Series, No. 176). An English translation is presented of a paper which appeared in Stahl und Eisen, 1934, vol. 54, Aug. 9, pp. 822–827 (*see* Journ. I. and S.I., 1934, No. II., p. 504).

Utility Briquettes from Waste Slack. H. B. Farmer. (Foundry Trade Journal, 1944, vol. 73, May 18, pp. 55–56). The preparation of a fuel to replace either large coal or gas for such foundry purposes as cupola lighting

and ladle drying is described. The mixture for making the briquettes consists of 48 lb. of small coal or slack below $\frac{1}{4}$ in., 6 lb. of cement, 3 pints of sawdust and $7\frac{1}{2}$ pints of water. A straw-like material named " shives," which is a waste product of the flax industry, can be used in place of the sawdust. The mixture is rammed in simple rectangular wooden moulds, and the briquettes thus produced are air-dried for 5–6 days. Working alone a youth can make 30 briquettes per hr.

The " Caking " of Coal. J. G. King. (Fuel in Science and Practice, 1944, vol. 23, May–June, pp. 61–64). The Gray-King assay scale for expressing the caking power of a coal is explained. Non-caking coals in which no sign of coherence develops in the carbonised product are designated by the letter A. Coals which give a hard, compact, non-fissured coke of the same volume as the original coal are termed G. The intermediate letters B to F are used to designate coals from which the cokes decrease in friability in this order. Coals of coking power higher than that represented by type G are mixed with ignited electrode carbon, and the proportion is varied until a coke of type G is obtained. A coal which requires 1 g. of carbon in the 20 g. treated is designated G_1; a coal which requires 2 g. is designated G_2, and so on. The limiting value for British coals is probably G_{12}. The scale from A to G_{12} thus provides 19 types covering the entire range of British coals. The effects of pyritic sulphur and of hydrogen on the caking power of coal as measured by the above scale are discussed.

New Plant for Purification of Coke Oven Gas Placed in Operation by Ford. (Industrial Heating, 1944, vol. 11, Mar., pp. 410–414). The Thylox sulphur recovery plant at the Ford Motor Company's works at Dearborn is described (*see* p. 2 A).

PRODUCTION OF IRON

Blast-Furnace Moisture Control Study. J. J. Alexander. (Blast Furnace and Coke Oven Association of the Chicago District and Eastern States Blast Furnace and Coke Oven Association : Blast Furnace and Steel Plant, 1944, vol. 32, Mar., pp. 346–351). *See* p. 2 A.

Increased Blast Furnace Capacity and How Accomplished. G. T. Williams and B. M. Stubblefield. (Yearbook of the American Iron and Steel Institute, 1943, pp. 95–108). *See* Journ. I. and S.I., 1944, No. I., p. 5 A.

Stepping Up Blast Furnace Blowouts. J. D. Knox. (Steel, 1944, vol. 114, Apr. 24, pp. 110–112, 144). Methods employed at American iron-works to reduce the time required for removing furnace bear at the end of a blast-furnace campaign are described. One method is to use pneumatic drills to bore a test hole horizontally through the furnace foundation about 12 ft. below the hearth level until red-hot brickwork is encountered. The boring is then continued with the oxygen lance. If no iron runs out, a new test hole is made about 2 ft. higher than the first one ; if necessary this procedure is repeated until a level is reached at which most of the bear can be drained out in the molten state. The time taken from beginning the last cast to the complete draining of the bear was about 36 hr.

Equilibria in the Reduction of Chromic Oxide by Carbon, and Their Relation to the Decarburization of Chromium and Ferrochrome. F. S. Boericke. (United States Bureau of Mines, Mar., 1944, Report of Investigations No. 3747). The removal of carbon from high-carbon ferro-chromium is an important and an expensive process. Several methods

have been advocated, but it has been difficult to judge them because the data concerning the carbides of chromium are conflicting. The present report covers an investigation in which : (1) All the carbides of chromium mentioned in the literature were prepared in reasonably pure form ; (2) the specific heats and entropies of the carbides were determined ; (3) the high-temperature heat contents of the carbides were measured ; and (4) equilibria were determined for the reactions occurring when reducing chromic oxide to pure chromium with carbon.

Design of Powder Metallurgy Parts. M. T. Victor and C. A. Sorg. (Metals and Alloys, 1944, vol. 19, Mar., pp. 584–589). The limitations of the powder-metallurgy process of manufacture are pointed out and some design principles which exploit to the full the advantages of the process are explained.

Presses and Processes for Metal Powder Products. E. V. Crane and A. G. Bureau. (Electrochemical Society, Apr., 1944, Preprint No. 85–14). A comprehensive review is presented of the present position in the development of powder metallurgy in the United States.

The Determination of Particle Size in Powder Metallurgy. P. R. Kalischer. (Electrochemical Society, Apr., 1944, Preprint No. 85–15). Four methods of determining the sizes of particles of very fine powders are described and discussed ; these are : with the microscope, by elutriation in air, by elutriation in a liquid, and by gravitational fractionation. The last is found to be the best and is very accurate.

Bonding Metal Particles by Heat Alone without Pressure. L. Delisle. (Electrochemical Society, Apr., 1944, Preprint No. 85–16). The results of an examination under the microscope and of physical tests on specimens made of iron, copper and silver powders by sintering in hydrogen for 3 hr. at various temperatures are reported. The particle sizes studied ranged from a few microns to 1 mm. in dia. The bond and density of the specimens increased with decreasing particle size. Cold-working the powder appeared to lower the temperature at which bonding starts ; the addition of a little graphite to electrolytic iron seemed to have a similar effect.

FOUNDRY PRACTICE

(Continued from pp. 37 A–41 A)

Views on Foundry Training. R. F. Coates. (Institute of British Foundrymen : Foundry Trade Journal, 1944, vol. 73, June 8, pp. 105–109). Recommendations for increasing the number of young men entering the foundry industry and providing for their training have already been made. In the present paper a plan for foundry training is put forward and discussed.

The Laboratory and the Foundry. D. Fleming. (Institute of British Foundrymen : Foundry Trade Journal, 1944, vol. 72, Apr. 27, pp. 345–350, 354 ; vol. 73, May 4, p. 7). The relationship between the foundry laboratory and the other foundry departments is discussed, and the true functions of the laboratory are explained with some notes on the application of spectrography and polarography for the analysis of metals.

Some Fundamental Relations within the Cupola. W. Pennington. (Transactions of the American Foundrymen's Association, 1944, vol. 51, June, pp. 980–1018). The reactions taking place in a cupola are discussed and formulæ are derived for calculating the composition of the waste gases, the fuel burning rate, the melting rate and the ratio of the carbon taken up by the iron to that which is burned.

The Side Feeding of Steel Castings. A Note on the Influence of the Mechanism of Freezing. B. Gray. (Iron and Steel Institute, 1944, this Journal, Section I). After agreeing with the view that whirl-gate and atmospheric heads largely depend for their success on the control of the direction of solidification by the temperature gradient, it is suggested that the results are also influenced strongly by factors arising from the mechanism of freezing of the steel. That subject has been much studied in chilled ingots, but very little in steel castings. Four experiments are described with 4-in. square bars cast in various ways. It is pointed out that the rate of increase in wall thickness is less on vertical than on horizontal walls, and different again when the head is applied at the bottom, that the crystalline structures also differ and that two forms of solid result. It is suggested that convection currents play an important part, and that they, in turn, are affected by the size and shape of the casting. The distribution of the secondary segregated material of lower melting point has important effects in feeding. Atmospheric pressure is also important. The mechanism of freezing explains why side heads are less effective with cold steel. The paper concludes with an assessment of the efficiency of various methods of feeding when considered in the light of the experiments described. Taylor and Rominski (*Transactions of the American Foundrymen's Association*, 1943, vol. 50, Mar., pp. 711–717) described the occurrence of unsoundness in a 2-in. plate cast with an atmospheric head. An explanation, based on differential freezing, is put forward in an Appendix.

Southern Bentonite in the Steel Foundry. N. J. Dunbeck. (Transactions of the American Foundrymen's Association, 1944, vol. 51, June, pp. 929–934). The differences between foundry sands prepared with western bentonite and with southern bentonite, produced in the Mississippi area and Wyoming respectively, are discussed. Western bentonite swells in water to about ten times its dry volume, whilst southern bentonite swells little more than ordinary clays; the latter settles rapidly in water. Cores for steel castings made with southern bentonite are strong and hard, but their collapsibility is greater than when western bentonite is used.

Moulding Sands and Gases in Relation to Casting Defects. G. W. Nicholls. (Institute of British Foundrymen: Foundry Trade Journal, 1944, vol. 73, June 1, pp. 85–91; June 8, pp. 111–114, 116). The effect of changes in the properties of moulding sand mixtures on the quality of iron castings is discussed. All sands require a moisture content of 5–6% for green sand work and 8–10% for dry sand work. The exact amount depends largely on the grain size of the sand. The amount also depends on the quantity of coal dust added. The effects of coal dust additions to moulding sands at high temperatures are indicated by the following test results: (1) At 1200° C. 10% by volume of coal dust added to the sand produced 390 c.c. of gas from 10 g. of the mixture; (2) with no coal dust the same sand mixture generated 65 c.c. of gas. The coal dust addition slightly increased the green strength at room temperature and decreased the permeability. Some typical casting defects due to the generation of too much gas by too much core oil, and to bad venting, are described and illustrated.

A.F.A. Subcommittee on Sintering Test Reports. (American Foundryman, 1944, vol. 6, Mar., pp. 2–4). A summary is presented of the Report by a Sub-Committee of the Foundry Sand Research Committee of the American Foundrymen's Association; it deals with the adherence of moulding sand to iron castings and with sand sintering tests. In some cases sand adheres to iron by fusing on to it; in other cases the iron penetrates the mould wall and the sand is trapped in the casting.

Elevated Temperature Studies of Foundry Cores and Core-Making Materials. E. Pragoff, jun., and C. P. Albus. (Transactions of the American Foundrymen's Association, 1944, vol. 51, June, pp. 935–971).

The hot strength, retained strength and expansion of the following types of sand cores were studied : (1) New sand cores bonded with organic binders without any clay ; and (2) black sand cores containing clay, bonded with organic binders. The method of measuring the hot strength of moulding sands is applicable to type (2) cores but not to type (1). Tests should be made at intervals of 100° F., rather than at 500° F. intervals. In new sand cores almost all the strength provided by organic binders is lost after 10 min. at 1000° F. Retained strength tests are valuable when selecting materials to make cores which are easily knocked out. The hindered-expansion method of determining the expansion of moulding sand, as now developed, is not suitable for testing new sand cores containing organic binders alone ; it is practical for control tests on black sand cores containing clay.

Mechanical Aids to Core Production. J. Blakiston. (Institute of British Foundrymen : Foundry Trade Journal, 1944, vol. 73, May 18, pp. 43–48, 56 ; May 25, pp. 63–66). Descriptions are given of mechanical methods by which core production in foundries has been made more efficient. Steel band conveyors, gravity roller conveyors and light railways are discussed and recommendations on the equipment for core benches and the layout of the core plant are made.

The Bonding Properties of Mixtures of Petroleum Extracts and Linseed Oil and of the Extracts Themselves. W. Davies and W. J. Rees. (Iron and Steel Institute, 1944, this Journal, Section I). The results obtained in this investigation show that petroleum extracts, produced at refineries in Great Britain as a by-product in the purification of the lubricating-oil fraction from the distillation of crude petroleum, can be used satisfactorily to replace at least 40% of the linseed oil in core-sand mixtures. This replacement is advantageous economically, as the petroleum extracts are at present much lower in price than linseed oil, and there is the additional advantage of utilising a home-produced by-product. Complete replacement of linseed oil by petroleum extract was unsatisfactory in the series of tests made.

Job Analysis and Time Value Predetermination as Applied to Pattern-making. W. D. Walters. (Transactions of the American Foundrymen's Association, 1944, vol. 51, June, pp. 869–872). A procedure for estimating the time required to make patterns is described. This is based on dividing patterns into groups, each group representing a design type, and then building up a time-study card for each group from past experience. When a new pattern has to be made the card representing its type is examined and an experienced patternmaker is able to make the necessary allowances for dimensional differences and thus compute fairly accurately the man-hours required.

A Study of Molding Methods for Production of Sound Castings. F. G. Sefing. (American Foundryman, 1944, vol. 6, Apr., pp. 66–70). Recommendations are made relating to moulding practice to eliminate defects in castings. The total area of the gates should be sufficient to give the maximum pouring speed without washing the sand. The gates should be rectangular rather than square in section. The section of the riser connection should not exceed one-third of that of the casting. In some cases the riser extends below the connection so that there is enough metal present to ensure it freezing last. In general, good mould design ensures directional solidification, so that freezing begins at the thinnest section and progresses towards the thickest section.

Heading and Gating of Malleable Iron Castings. A. J. Klimek. (American Foundryman, 1944, vol. 6, Apr., pp. 49–51). Examples showing the positions of gates and risers in small malleable iron castings are described and illustrated.

Skin Drying Molds with Infra-Red Lamps. H. B. Voorhees. (American Foundryman, 1944, vol. 6, Mar., pp. 13–14). A brief description is given of the mould-drying practice at an Indiana foundry. Banks of 250-W. lamps held on wooden frames are used, and these dry the moulds to a depth of about 1 in. in 45 min., consuming a little less than 1 kW. per sq. ft. of mould surface. Moulds with narrow vertical sides are difficult to dry if they are more than 6 in. deep. Before switching off the current it is advisable to see that all lamps are burning and, if any bulbs have burnt out, the mould must be carefully examined for any spots which may be insufficiently dried.

Molds Laundry Machinery Castings. P. Dwyer. (Foundry, 1944, vol. 72, Mar., pp. 100–102, 162). An illustrated description is given of the foundry practice of the American Laundry Machinery Co., at Rochester, New York.

Iron Roll Manufacture. G. L. White. (Canadian Metals and Metallurgical Industries, 1944, vol. 7, Mar., pp. 16–20). A description is given of the foundry practice at the Dominion Engineering Works, Ltd., Lachine, Quebec, where cast-iron rolls are made. Two cupolas, a 25-ton and a 20-ton air furnace, are used. The air furnaces are preferred because closer temperature control is possible and the charge can be held after it is melted while analyses and chill tests are made. All moulds are poured vertically in pits in the foundry floor ; the drag contains the bottom neck and ingate, the cope provides for the top neck and the riser, and the down-gate is fastened on the outside of the drag. The cope is designed to slide inside the chills ; it can therefore be set at different heights to produce different body lengths of roll with the same chills. The cope is permitted to slide down into the chills with the contraction of the iron, and the top neck is not held rigidly in place, thus avoiding cooling strains on the rolls. The ingate is brought in at a tangent just above the wobblers in the drag ; this causes the metal to rise up the mould with a swirling action, which is maintained until it reaches the top. In a large mould the vortex thus caused may be up to 12 in. deep. The technique for casting a roll with a high-alloy iron face and grey iron for the necks and core is also described.

Four-Part Cheek Method of Producing Cast Iron Cylinders. R. Hendry. (American Foundryman, 1944, vol. 6, Apr., pp. 38–42). A detailed illustrated description is given of a method of preparing the mould for casting large low-pressure steam-engine cylinders. A four-part cheek method was employed, as it permitted the internal cores to be set in place before the mould itself was completed ; it also eliminated the use of chaplets at vital parts of the casting.

Centrifugal Casting Methods. N. Janco. (Iron Age, 1944, vol. 153, Mar. 30, pp. 42–45). Types of moulds and pouring techniques for making centrifugal castings are described. Sand moulds are used when the shape of the casting is irregular or when only a few castings of a particular size are to be made. Permanent moulds are generally made of high-strength alloy cast iron, and a refractory wash is usually sprayed on the inside wall to a thickness of about $\frac{1}{32}$ in. A series of curves is presented showing the centrifugal force generated when spinning moulds from 1 to 18 in. in dia. at speeds of 100–3000 r.p.m.

PRODUCTION OF STEEL

Expansion Program of the Steel Industry. J. A. Kinney. (Yearbook of the American Iron and Steel Institute, 1943, pp. 53–82). Three periods in the expansion of the American iron and steel industry are reviewed and

production and capacity statistics for the iron and steel furnaces are presented. The three periods are the twenty years ending December 31, 1940, the years 1941 and 1942, and the expansion programme of the War Production Board after 1942.

Wartime Scrap Problems. F. E. Vigor. (Yearbook of the American Iron and Steel Institute, 1943, pp. 222–229). The increased difficulties in obtaining steel scrap in the United States is discussed with special reference to methods of preparing turnings (*see* Journ. I. and S.I., 1944, No. I., p. 49 A).

Wartime Production of Constructional Steels in the Basic Electric Furnace. H. W. McQuaid. (Yearbook of the American Iron and Steel Institute, 1943, pp. 202–221). *See* Journ. I. and S.I., 1944, No. I., p. 13 A.

The Conservation of Critical Materials. C. H. Herty, jun. (Yearbook of the American Iron and Steel Institute, 1943, pp. 271–280). Methods recommended by the American Iron and Steel Institute and by various committees set up in the United States for reducing the consumption of manganese, aluminium, ferro-silicon and fluorspar in steelmaking are outlined. The lack of scrap has led to open-hearth furnace charges containing a high proportion of hot metal. With this practice it was found that the iron ore for the open-hearth furnace could consist mostly of soft Lake Superior ore, the proportion depending on the degree of fineness, the silica content and the amount of combined water. The extent to which alloying elements can be recovered from alloy steel turnings is discussed.

Plant Production Problems Presented by Sustained High Level Operations. E. C. Wright. (Yearbook of the American Iron and Steel Institute, 1943, pp. 109–119). Difficulties met with in increasing the production of steel in open-hearth furnaces under war-time conditions are discussed.

Increase in Open Hearth Production and How Achieved. A. P. Miller. (Yearbook of the American Iron and Steel Institute, 1943, pp. 120–161). Results of the efforts made in the United States to increase the production of steel are presented with tables and curves, and details of some of the measures taken are discussed ; these include : (1) Use of higher hot metal charges ; (2) accurately timing hot metal additions ; (3) charging the percentage of iron which, with a given type of ore, will give the optimum production ; (4) augmenting the ore with sinter when using higher iron charges ; (5) planning all operations in advance to prevent delays ; (6) using the charging ladles to full capacity whenever possible ; (7) providing adequate auxiliary charging and pit equipment ; (8) distributing scrap so as to provide uniform charges from heat to heat ; (9) using rapid slag control methods to obtain optimum control of the melting and refining practice ; and (10) adopting incentive systems to encourage increased production.

Steel Melting. A. H. Leckie. (Iron and Steel, 1944, vol. 17, May 18, pp. 385–390). Some possibilities of obtaining better fuel efficiency in open-hearth furnace practice are discussed. These fall under the following headings : (1) Keeping constant watch on the pressure in the melting chamber with more frequent use of the damper ; to achieve optimum results automatic damper control is necessary. (2) Better control of the gas flow, particularly during the refining period ; control of the temperature by cutting off the air should be eliminated as far as possible. (3) Good maintenance of the door jambs and arches, and cleanliness of the sills. (4) Insulation as a means of preventing heat losses and of sealing cracks to prevent infiltration. (5) Prevention of loss of gas during reversals.

Experiences with Arc-Furnace Roofs of Standard Bricks with Built-In Metal Cooling Collars. H. Müller. (Iron and Steel Institute, 1944, Translation Series, No. 177). An English translation is presented of a paper which appeared in Stahl und Eisen, 1943, vol. 63, Mar. 18, pp. 217–220 (*see* Journ. I. and S.I., 1943, No. II., p. 13 A).

Utilizing Alloy Steel Scrap. V. E. Zang. (Foundry, 1944, vol. 72, Mar., pp. 113, 134). The electric-furnace charging practice at a steel foundry where it was necessary to increase the proportion of scrap, particularly turnings, in the charge is described. (*See* p. 9 A).

Basic Practice Development in the Electric Arc Furnace. H. F. Walther. (Engineers' Society of Western Pennsylvania : Blast Furnace and Steel Plant, 1944, vol. 32, Mar., pp. 334–342). The development of electric-furnace steelmaking in the United States is reviewed and a detailed description is given of the working of a heat in a 70-ton basic-lined arc furnace to produce a low-alloy chromium-nickel-molybdenum steel.

The Rôle of Basic Slags in the Elimination of Phosphorus from Steel. R. L. Barrett and W. J. McCaughey. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1716 : Metals Technology, 1944, vol. 11, Apr.). The constitution of basic slags, the equilibrium diagram for the $CaO–SiO_2–P_2O_5$ system and the removal of phosphorus from steel are discussed. A diagram is also presented showing the probable equilibrium conditions in the two-component system the end-members of which are dicalcium silicate and tricalcium phosphate ; between these lie the two ternary phases nagelschmidtite and silicocarnotite. The great degree to which solid solution prevails in these four phases is significant. The homogeneity ranges of the four phases expressed in the form of the ratio $P_2O_5/(P_2O_5 + SiO_2)$ are as follows : Dicalcium silicate 0·0–0·27, nagelschmidtite 0·31–0·58, silicocarnotite 0·71–0·80, and tricalcium phosphate 0·89–1·00. It appears from this that when there is enough CaO present to combine with all of the SiO_2 and P_2O_5 in the orthosilicate ratio, these two components are almost completely interchangeable and the bonding between them and CaO is of a similar type regardless of the $P_2O_5/(P_2O_5 + SiO_2)$ ratio. This fact appears to be of major importance in the elimination of phosphorus from steel.

Variable Heat Flow in Steel. R. Jackson, R. J. Sarjant, J. B. Wagstaff, N. R. Eyres, D. R. Hartree, J. Ingham. (Iron and Steel Institute, 1944, this Journal, Section I). Methods for the calculation of variable heat flow have been devised which take into account the variable diffusivity of the material, latent heat of a change point and almost any surface conditions. Calculations made for the case of a steel ingot cooling in a mould also allowed for the radiative heat transfer across the air gap between ingot and mould and the different thermal properties of the two materials. The range of problems dealt with has been limited by the lack of adequate information on the thermal properties of steel. Two instruments, one mechanical and the other electrical, have been used for the calculation as well as numerical methods. The calculations show good agreement when compared with experimental results obtained both in the laboratory and on large-scale masses in industrial furnaces. A rapid approximate method of obtaining the central temperature of an ingot has been devised. A nomograph and slide rule are given for calculating the soaking time required for uniformity of temperature in industrial practice. The results suggest improvements in heating technique in industrial furnaces ; these are discussed.

Colloidal Physico-Chemical Methods for the Separation from the Carbides, of Slag Inclusions Precipitated from Steel. S. M. Gutman, P. A. Rehbinder, M. E. Lipetz and M. M. Rimskaya. (Iron and Steel Institute, 1944, Translation Series, No. 183). An English translation is presented of a paper which appeared in Comptes Rendus de l'Academie des Sciences de l'U.S.S.R., 1935, vol. 1, Feb. 11, pp. 308–312 ; it describes a method for separating slag inclusions present in carbon steels from the graphite arising from the previous decomposition of the iron carbides. The method is based on a selective dispersion and peptisation of the graphite.

The Solution and Evaluation of the Relationship between Costs and the Degree of Activity by the Punched Card System. A. M. Wolter and H. Brodmeier. (Archiv für das Eisenhüttenwesen, 1943, vol. 16, Jan., pp. 273–281). Methods of iron and steel works costing are explained in which the various process departments combine with the costs department to evolve a practical costing system using punched cards.

REHEATING FURNACES

Fuel Proportioning and Temperature Control Applied to Forge Furnaces. (Industrial Heating, 1944, vol. 11, Mar., pp. 378–386). The oil-fired reheating furnaces for forgings at the works of J. H. Williams & Co., Buffalo, New York, are described. There are 69 furnaces, ranging in hearth size from 108×47 in. down to $19 \times 13\frac{1}{2}$ in. They are all fitted with automatic air-oil proportioning equipment.

The Dependency of Scaling upon the Composition of the Gas Atmospheres, the Heating Period, the Temperature and the Gas Velocity. R. Bourggraff. (Iron and Steel Institute, 1944, Translation Series, No. 178). An English translation is presented of a paper which appeared originally in Stahl und Eisen, 1940, vol. 60, Feb. 15, pp. 129–137 ; Feb. 22, pp. 156–159 (*see* Journ. I. and S.I., 1940, No. II., p. 55 A).

FORGING, STAMPING AND DRAWING

Planned Grain Flow in Forgings. W. Naujoks. (Metals and Alloys, 1944, vol. 19, Mar., pp. 590–592). The manner in which rolling develops grain flow lines in ingots is described and the importance of forging in such a manner as to make the best use of the direction of these lines to produce the optimum properties in the finished part is discussed.

Upset Forging on a Welder. D. B. Wilkin. (Steel, 1944, vol. 114, Apr. 17, pp. 94–97, 100–102). An illustrated description is given of the development by the Cleveland Pneumatic Tube Company of the adaptation of flash butt welding machines for upset forging, in particular for making trunnion pins.

Processing Parts from Strip Steel in Progressive Dies. C. W. Hinman. (Steel Processing, 1944, vol. 30, Mar., pp. 162–164). The design of a three-station progressive die for producing large numbers of channel-shaped clips from steel strip is described.

Dies for Drop Forging. E. W. Mace. (Mechanical World, 1944, vol. 115, Jan. 7, pp. 5–6 : Steel Processing, 1944, vol. 30, Mar., pp. 154–155). The operation of multi-impression dies for making components such as brake levers from bars is described and discussed.

Reclaiming 75 mm. A.P. Shot by Forging. C. C. Barrenbrugge. (Iron Age, 1944, vol. 153, Apr. 13, pp. 71–73). A description is given of the process which was developed to convert solid armour-piercing 75-mm. shells into hollow high-explosive shells with a cavity 4 in. deep and $1\frac{1}{2}$ in. in dia. This was done in three stages in an upset forging press after annealing at 1200° F. and reheating to 2100° F.

Fabrication of Bofors Top Carriage Gun Table at Midland Steel Products Company. W. N. Robinson. (Steel Processing, 1944, vol. 30, Mar., pp. 147–153). The sequence of processes developed by the Midland Steel

Products Company, Ohio, for making gun tables for the 40-mm. Bofors gun is described and illustrated. The operations include cleaning, stamping, forming, heat-treating, machining and welding.

Rod Drawing, Straightening and Polishing Machine. (Engineer, 1944, vol. 177, June 16, pp. 473–474). A brief description is given of a combined and continuous rod-drawing, cutting-off, straightening and polishing machine for drawing low-carbon steel rods of up to $\frac{1}{2}$ in. in dia. The output speed is about 80 ft. per min.

Drawing Fine Uncoated Steel Wire. R. R. Preston. (Wire Association : Steel, 1944, vol. 114, Mar. 27, pp. 97, 132). The cleaning, liming, lubricating and drawing of uncoated steel wire to 0·036 in. dia. is described.

ROLLING-MILL PRACTICE

(Continued from pp. 45 A–46 A)

Friction. L. D. Colam. (Iron and Steel, 1944, vol. 17, May 18, pp. 391–396). The causes and elimination of friction losses in bearings typical of a 10-in. or 12-in. five-stand three-high bar mill are discussed, and information is given on actual savings effected by centralised lubrication systems in some American rolling mills.

Production of Steel Plates. C. L. McGranahan. (Yearbook of the American Iron and Steel Institute, 1943, pp. 83–94). Particulars are given of the increase in the plate-rolling capacity of the steelworks in the United States which was achieved for war purposes. The conversion of strip mills for the production of plates is described.

Electronic Detection of Pinholes. H. J. Hague. (Steel, 1944, vol. 114, Mar. 20, pp. 108,–110). A description is given of a photo-electric cell apparatus for detecting holes as small as 0·01 in. in steel strip. The apparatus is designed for incorporation in continuous strip mills running at up to 1000 ft. per min.

Recording and Indicating Instruments for Steel Mill Service. P. E. Twiss and R. M. Powell. (Blast Furnace and Steel Plant, 1944, vol. 32, Mar., pp. 356–357). Descriptions are given of a recording voltmeter, an indicating voltmeter and an indicating ammeter specially designed for service in rolling mills.

HEAT TREATMENT

(Continued from pp. 47 A–48 A)

Heat Treatment of Large Steel Forgings in Controlled Atmospheres. O. E. Cullen. (Steel Processing, 1944, vol. 30, Mar., pp. 173–177). An illustrated description is given of a gas-fired radiant-tube furnace, 13 ft. 6 in. long × 10 ft. wide × 12 ft. 6 in. high, for heat-treating forgings, and the composition of suitable protective atmospheres is discussed.

Problems in Making and Heat-Treating Castings of an Air Hardening Steel. G. W. Johnson. (American Foundryman, 1944, vol. 6, Apr., pp. 64–65). An air-hardening chromium-nickel-molybdenum steel is recommended for castings having thick and thin sections which are to be hardened throughout with little or no distortion. A preliminary stress-relieving treatment is generally given before the gates and risers are cut off. To permit machining, a carefully controlled annealing treatment first at 1600° F. and then at 1250° F. is applied. After machining, the castings are hardened by cooling in air from 1650° F. and then tempered at 900–1100° F.

Carburizing and Heat-Treating Transmission Parts for Naval and Air Force Equipment. (Industrial Heating, 1944, vol. 11, Mar., pp. 370–376). An illustrated description is given of an oil-fired continuous furnace for heat-treating gears and other parts for United States Navy and Air Force equipment. Four parallel sets of rails pass through the furnace, along which four sets of boxes containing the parts are moved by hydraulic pushers.

Advanced Heat Treating Techniques. R. C. Gibbons. (Steel, 1944, vol. 114, Mar. 27, pp. 82–83, 124–126). Brief descriptions are given of some of the controlled-atmosphere continuous furnaces and induction-hardening equipment installed by the Bendix Aviation Corporation, which enabled a great increase in the production of aircraft parts to be made.

Why Carburize? D. McPherson. (Machinery, 1944, vol. 64, June 1, pp. 605–607). The advantages and disadvantages of case-hardening are critically reviewed. That many thousands of case-hardened parts are capable of carrying heavy loads and of resisting wear is not necessarily a criterion of excellence for such parts, but may only be evidence of the provision of a very large load safety factor by nervous ingenious designers. In many cases in industry a step forward would be made if case-hardening steels were discarded in favour of direct-hardening alloy steels.

Industrial Electric Furnaces. Part I. Determining Factors in Selection of Electric Furnace Types. V. Paschkis. (Industrial Heating, 1944, vol. 11, Jan., pp. 52–60). The applications of arc furnaces, directly heated resistor furnaces, indirectly heated resistor furnaces and of high-frequency induction heating are discussed.

Industrial Electric Furnaces. Part II. Advantages and Disadvantages of Electric Furnaces. V. Paschkis. (Industrial Heating, 1944, vol. 11, Feb., pp. 226–238). A comparison is made between electrically heated and fuel-fired furnaces so as to show the advantages and disadvantages of the former.

Industrial Electric Furnaces. Part III. The Primary Heat Problem of Electric Furnace Design. V. Paschkis. (Industrial Heating, 1944, vol. 11, Mar., pp. 362–368). A method is proposed for determining the type and size of electric furnace which will have the lowest over-all operating cost when the following factors are known : (a) The output desired ; (b) the material involved ; (c) the maximum permissible temperature difference between the surface and core of the material at the end of the heating time ; and (d) the maximum permissible rate of heating.

Oster Plant Heat Treat Utilizes Lead and Salt-Bath Pot Furnaces. (Industrial Heating, 1944, vol. 11, Feb., pp. 214–218). A brief description is given of the heat-treatment plant of the Oster Manufacturing Company, Cleveland, Ohio, which has two gas-heated lead-baths, electrically heated salt-baths and small gas-fired furnaces for the heat treatment of stocks, dies, pipe-threading tools and lathe parts.

Sal-Way Steel Treating Company Employs Salt-Bath Furnaces Exclusively. (Industrial Heating, 1944, vol. 11, Feb., pp. 292–296). The heat-treatment plant of the Sal-Way Steel Treating Company, Detroit, is briefly described. This company has seventeen salt-bath furnaces electrically heated by immersed electrodes for heat-treating high-speed steels and tools.

Hardening NE 8745 Steel. D. E. Roda and F. C. Brautigam. (Iron Age, 1944, vol. 153, Apr. 6, pp. 42–46). A series of experiments to determine the optimum hardening and tempering practice for rifle parts made of steel NE 8745 is described. This is a nickel-chromium-molybdenum steel containing 0·45% of carbon.

Modern Practice in Surface Hardening. Controlled Gas Carburizing and Diffusion Cycles, F. E. Harris. (Metal Progress, 1944, vol. 45, Mar.,

pp. 484–486). Factors controlling the rate at which steel takes up carbon in the gas-carburising process are discussed. The rate of carbon absorption varies inversely with the square of the elapsed time. In a gas-carburising furnace the pressure requirements are met by a flow of prepared gas very low in carbon, to which is added sufficient natural gas to supply the amount of carbon required. In some cases the carbon concentration at the surface of the steel may be too high; the supply of natural gas can then be cut off and heating continued so as to allow diffusion into the steel to take place.

Modern Practice in Surface Hardening. Supposed " Graphite " in Carburized Cases. J. Welchner. (Metal Progress, 1944, vol. 45, Mar., pp. 486–487). Theories for the formation of a foreign grain boundary material found at the surface of case-hardened steels of the NE 9000 series are put forward. This was previously discussed by the author and R. W. Roush (see Journ. I. and S.I., 1944, No. I., p. 17 A). When this material was examined under polarised light certain portions appeared to be anisotropic like alumina, whilst the remainder was removed by hydrofluoric acid, which identified it as silica. There is thus evidence that it is not graphite.

Modern Practice in Surface Hardening. Chromium Plating, Nitriding, Carburizing of Tool Steels. J. P. Gill. (Metal Progress, 1944, vol. 45, Mar., pp. 488–490). Methods of chromium-plating, nitriding and case-hardening tool steels are reviewed, with notes on the particular applications for which each of these processes is best suited.

Modern Practice in Surface Hardening. Utility of the Hardenability Test on Steels for Carburizing. O. W. McMullan. (Metal Progress, 1944, vol. 45, Mar., pp. 490–492). The value of the Jominy end-quench test and of other hardenability tests for carburising steels is discussed (see preceding abstract).

Modern Practice in Surface Hardening. Differential Hardening with High Frequency Current. F. F. Vaughn. (Metal Progress, 1944, vol. 45, Mar., pp. 493–494). The principles of induction hardening are explained, with data on the A.C. frequencies required to produce different case depths.

Modern Practice in Surface Hardening. Putting Flame Hardening to Work. G. T. Williams. (Metal Progress, 1944, vol. 45, Mar., pp. 494–496). The equipment for flame-hardening is described and the advantages, limitations and cost of the process are discussed.

Controlled Atmospheres for Bright Hardening. C. E. Peck. (Metals and Alloys, 1944, vol. 19, Mar., pp. 593–599). The following factors relating to atmospheres for bright, or scale-free, hardening of steel are discussed : (1) The composition and cost of suitable atmospheres ; (2) equipment for producing the atmospheres ; (3) atmosphere equilibria and methods of determining the atmosphere required for a given steel at a given temperature ; (4) the types of steel which can be bright-hardened ; and (5) the furnace equipment most suitable for controlled-atmosphere bright-hardening.

Gas Quenching. W. Lehrer. (American Society for Metals : Steel, 1944, vol. 114, Apr. 10, pp. 98–99, 134–136). The author's paper on the heat treatment of low-alloy welded steel tubes for aircraft is reproduced (see Journ. I. and S.I., 1944, No. I., p. 86 A).

Amount of Martensite in Quenched Steel Influences Properties After Tempering. B. F. Shepherd. (Metal Progress, 1944, vol. 45, Mar., pp. 503–507). Diagrams are presented in which the end-quench hardenability of steel is related to the " critical hardenability," i.e., the diameter of bar which will have a 50% martensitic structure at the centre after quenching in still oil, and to the hardness obtained after tempering at various temperatures. The application of these diagrams for determining the cooling rates and tempering temperatures for obtaining the desired surface and core

hardness is explained. Much of the published test data on the relationship between mechanical properties, hardness and tempering temperature give a wrong impression, because they are only valid for the particular percentage of martensite that existed in the tensile test section as quenched.

Sub-Zero Stabilizing of Steel Gages and Parts. H. A. Knight. (Metals and Alloys, 1944, vol. 19, Mar., pp. 610–614). The processes, which include refrigeration, used by a number of American firms to stabilise gauges blocks, mandrels and spindles, are reviewed. There appears to be no uniformity in the treatments, the low temperatures employed varying between −50° and −120° F. In some cases the cycle of cold treatment and tempering is repeated six times and takes about 48 hr.

Sub-Zero Treatment of High-Speed Steels. S. M. DePoy. (Iron Age, 1944, vol. 153, Apr. 13, pp. 52–55). The results of machining tests on a number of tungsten-molybdenum-chromium-vanadium high-speed steel tools the heat treatment of which included cooling to sub-zero temperatures are reported. Increased tool life was obtained in all cases by including the refrigeration treatment. For high-speed steel, temperatures down to −100° F. or even lower are necessary, but for carbon and low-alloy steels, temperatures of −40° to −80° F. are sufficiently low to obtain improvements.

WELDING AND CUTTING

Atomic Hydrogen Welding. P. H. Take. (Canadian Welding Society : Canadian Metals and Metallurgical Industries, 1944, vol. 7, Apr., pp. 33–34, 40–41). The applications of atomic hydrogen welding and its advantages are discussed and a description of the process and the equipment required is given.

Arc Welding Electrodes. W. Andrews. (Welding, 1944, vol. 12, Apr., pp. 186–193; May, pp. 245–248; June, pp. 266–270). A comprehensive survey of welding electrode manufacture is presented in which the various types of electrodes and their particular characteristics are clearly defined.

Tests on Mild Steel Electrodes. D. M. Kerr. (Welding, 1944, vol. 12, June, pp. 282–287). Tables are presented giving the results of tests on six makes of electrodes from 12 S.W.G. to $\frac{3}{8}$ in. in dia. at low, medium and high current settings. The tests were made to determine : (a) The melting-off rate for each make and size at each of the settings ; and (b) the weight of metal deposited in each case. The average proportions of metal deposited out of the total melted off were 82%, 79% and 75% for the low, medium and high current settings, respectively. The product of the current and the melting-off rate for any electrode was found to be a constant.

Strip Mill Butt-Flash Welding. (Iron Age, 1944, vol. 153, Mar. 30, pp. 56–58). An illustrated description is given of a large butt-flash welding machine for use in continuous strip mills for welding together the ends of coils of steel strip. The machine will weld strip from 0·075 to 0·187 in. thick and from 18 to 80 in. wide.

Peening—Its Effect on Relief of Residual Stresses, Distortion and Mechanical Properties of Welds. W. Spraragen and M. A. Cordovi. (Welding Journal, 1944, vol. 23, Mar., pp. 121-S–144-S). A comprehensive review of the American literature to July, 1943, and of that of other countries to January, 1941, on the effect of peening on welds is presented. The bibliography contains 148 references.

CLEANING AND PICKLING OF METALS

Gas-Pickling and Coating of Cold-Rolled Strip. R. F. Renkin. (Steel, 1944, vol. 114, Mar. 27, pp. 102–104). A description is given of a continuous galvanising plant at the works of the Sharon Steel Corporation, an interesting feature of which is the gas-pickling equipment. The strip passes first through a preheating furnace 50 ft. long × 4 ft. wide, in which it is directly heated by gas burners. It then enters the muffle of the gas-pickling furnace, which is made of alloy steel sections with a total length of 50 ft. and a width of 30 in.; this is externally heated by gas burners mounted in the furnace enclosure. The pickling gas, which passes through the muffle in the opposite direction to the strip, is generated by mixing the products of combustion of burnt natural gas and burnt hydrogen chloride gas. The plant is capable of pickling and galvanising cold-reduced rimming-steel strip 20 in. wide × 0·015 in. thick at about 125 ft. per min.

Industrial Metal Finishing. H. Silman. (Sheet Metal Industries, 1943, vol. 18, Dec., pp. 2121–2125; 1944, vol. 19, Feb., pp. 309–317; Mar., pp. 467–473; Apr., pp. 653–662; May, pp. 841–851). Continuation of a series of articles (*see* Journ. I. and S.I., 1944, No. I., p. 93 A). Automatic plants for degreasing shallow and small cup-shaped pressings are described, with notes on the alkalies employed, their efficiency, and on the use of wetting agents. Brief information on electrolytic alkaline cleaning, continuous plants for cleaning strip and for washing and drying shell cases is given. In Part V. decorative and light-duty colour finishes to metals are dealt with. The processes described include : (*a*) The " Electrocolour " process in which an organic copper solution is employed ; (*b*) the Bower-Barff process in which the steel is heated to about 800° C. for 20 min. first in air, then in superheated steam and finally in a producer-gas atmosphere ; this first forms a coating consisting of a mixture of Fe_2O_3 and Fe_3O_4 which is finally converted entirely to Fe_3O_4 ; (*c*) caustic alkali-nitrate processes ; (*d*) phosphatising, including Bonderising, Granodising and phosphatised zinc coatings ; and (*e*) coating with metals such as brass, cadmium, copper and aluminium with subsequent chemical treatment to obtain particular colours by the formation of salts.

Submerged Heating Speeds Pickling. T. E. Lloyd. (Iron Age, 1944, vol. 153, Mar. 23, pp. 57–60). A detailed description is given of the burners, ignition system and gas-air mixture control used for the submerged heating of pickling tanks.

Treatment of Spent Pickle Liquor. H. Swindin. (Institution of Chemical Engineers : Iron and Coal Trades Review, 1944, vol. 148, May 19, pp. 753–755). A comprehensive summary of methods of treating spent pickle liquors is presented. The treatments described include the production at a profit of iron oxides, pigments, copperas and solutions of iron salts.

COATING OF METALS

Conserve Your Cutting Tools, Gages and Dies by Chromium Plating. W. Whalen. (Steel, 1944, vol. 114, Jan. 17, pp. 103, 120–121). Some examples are given of the increased tool life obtained by chromium plating twist drills, milling cutters and pressing dies.

Porous Chromium Plating Diesel Cylinder Liners. (Iron Age, 1944, vol. 153, Apr. 6, pp. 50–53). The process of chromium-plating cylinder liners developed by the Van der Horst Corporation of America is described. The liners are first electrolytically etched in chromic acid solution and then put in the plating tank, the electrolyte for which contains trivalent and hexavalent chromium. The current consumption is about 15 amp.-hr. per sq. in. of surface for a 0·015-in. deposit. The plated liner is then returned to the etching tank for anodic treatment to remove some of the chromium, thus leaving a porous surface, the function of which is to retain lubricating oil. Cylinder liners for Diesel engines treated by this process have an exceedingly long life.

Production Phases of Hot Dip Galvanizing. W. G. Imhoff. (Steel, 1944, vol. 114, Mar. 13, pp. 110–112). Data accumulated in hot-dip galvanising practice are presented and discussed. If the galvanising pot contains 20 lb. of zinc per lb. of galvanised article produced, the heat requirements of the pot will be about 10,000 B.Th.U. per sq. ft. of heating area. As the quantity of zinc in relation to production is decreased the product will extract heat at a higher rate, so that the heat supply must be increased to compensate for this. At 15 lb. of zinc per lb. of product the rate of heat input is 12,000–15,000 B.Th.U. per sq. ft. of heating area ; if this rate is exceeded the life of the pot will be shortened by corrosion. The pot temperature should never exceed 900° F. The weights of coatings obtained on buckets for pot temperatures in the 800–900° F. range and for different immersion times are shown in a table.

Some Practical Facts about the By-Products Formed in Different Fields of Hot-Dip Galvanizing. W. G. Imhoff. (Wire and Wire Products, 1943, vol. 18, Nov., pp. 709–712, 732–734 ; Dec., pp. 772–774, 794, 795 ; 1944, vol. 19, Feb., pp. 115–117). The factors affecting the amount of dross and oxide skimmings formed in hot-dip galvanising are discussed. The amount of dross formed varies considerably with the type of article being dipped ; it is greatest with malleable iron castings and decreases in the following order : malleable iron castings, telegraph-pole fittings, structural work, wire, pipe, wire cloth, tanks, sheets and domestic hardware. The more open the texture of the metal surface and the longer the immersion time, the more dross will be formed.

Titanium Pre-Dip Process Increases Life of Zinc Coatings. (Industrial Heating, 1944, vol. 11, Mar., pp. 438–440). In preparing zinc-coated articles for a final phosphatising treatment it has been found that dipping in disodium phosphate gives excellent results, provided that the disodium phosphate contains a trace of titanium.

A New Electrolyte for Use in Electrotinning Lines. (Blast Furnace and Steel Plant, 1944, vol. 32, Feb., pp. 232–234). Some particulars are given of the new continuous electrolytic tinning plant of the Weirton Steel Co. The bath, containing a halogen electrolyte, is operated at 150° F. at a pH value of about 2·7. Depositing tin on continuously moving strip 32 in. wide at a coating weight of 0·5 lb. per base box requires a current density of 206 amp. per sq. ft. with the line running at 1000 ft. per min. For coatings of 0·75 and 1·0 lb. per base box the current densities are 309 and 412 amp. per sq. ft., respectively.

Electrotinning Operations. H. P. Munger. (Iron and Steel Engineer, 1944, vol. 21, Mar., pp. 53–60). A description is given of the new continuous electro-tinning plant installed by the Republic Steel Corporation (*see* p. 20 A).

Republic Uses Two Electrotinning Lines at Its Niles Plant. (Blast Furnace and Steel Plant, 1944, vol. 32, Mar., pp. 343–345). A brief description is given of the new continuous electrolytic tinning plant at the works of the Republic Steel Corporation (*see* p. 20 A).

The Use of Phosphate Coated and Lacquered Steel Sheet for Food Can Manufacture. L. Schuster. (Sheet Metal Industries, 1944, vol. 19, Mar., pp. 449–454 ; Apr., pp. 635–638, 640). An English translation is presented of a paper which appeared in Stahl und Eisen, 1942, vol. 62, Aug. 13, pp. 685–694 (*see* Journ. I. and S.I., 1943, No. I., p. 34 A).

Bonderizing. (Automobile Engineer, 1944, vol. 34, May, pp. 191–193). Immersion Bonderising and " Spra-Bonderising " as a means of increasing the adhesion and rust-resistance of paint, enamel or lacquer on steel are discussed, and the results of salt-spray and humidity tests on enamelled and lacquered panels with and without pretreatment by Bonderising are given.

Supplemental Protection for Black-Oxide Finishes. M. Weisberg and E. A. Parker. (Steel, 1944, vol. 114, Feb. 28, pp. 109, 136). Results are reported of salt-spray tests on oxide-coated steel sheets which had been given an additional coat of an oil, wax or varnish. The materials used, in decreasing order of the protection against salt-spray attack, were : (1) Mixtures of oil and grease, plus an inhibitor ; (2) inhibited oils ; (3) materials such as wax, lacquer and varnish which dried hard ; and (4) mineral oils.

Stretching the Life of a Nail Machine Crankshaft through Metal Spraying. J. Copp. (Wire and Wire Products, 1944, vol. 19, Mar., pp. 176–177, 191). Details are given of the cost and of the economies effected by repairing worn crankshafts of nail-making machines by metal spraying.

Dipping and Spraying Electrostatically. E. P. Miller. (Industrial Heating, 1943, vol. 10, Oct., pp. 1553–1562). A description is given of the necessary equipment and procedure for flowing, stoving and drying synthetic-resin coatings on metals with special reference to the removal of blobs from the drain-off points. This process is called " electrostatic detearing " and was recently described by H. P. Ransburg (*see* Journ. I. and S.I., 1944, No. I., p. 100 A). After dipping the article, it is carried on a conveyor over a draining-board and allowed to set until all flow of the coating has practically ceased ; it is then earthed and carried over an insulated grid charged at a high voltage ; this static charge attracts surplus coating material to the grid. This method has achieved considerable success in finishing coatings of phenol-formaldehyde varnish on steel cartridge cases.

The Application of Radiant and Inductive Heating to Industrial Processes. L. J. C. Connell. (G.E.C. Journal, 1944, vol. 13, Feb., pp. 10–32). The theories governing the transfer of heat by conduction, convection and radiation are explained and the merits and limitations of the three methods for industrial purposes are compared. The types of lamp and the design of reflectors used in Great Britain and the United States for radiation heating are described, with data on the intensities obtainable from single lamps and banks of lamps in trough reflectors. Several industrial applications of radiant heating, *e.g.*, for drying paint, varnish, foundry moulds and textiles, are described. The concluding part of the paper deals with the theory and practice of induction heating.

Infra-Red Heating. I. J. Barber. (Steel, 1944, vol. 114, Jan. 17, pp. 76–77, 110–116). Some examples of applications of heating by infrared rays in United States industries are described and illustrated. These include : (a) Baking paint on flat steel sheets used in oil-furnace construction ; (b) expanding bronze gears to fit them over shafts ; (c) heating the seams of submarine plates prior to welding them in very cold weather ; (d) heating degreased metal surfaces prior to paint spraying ; and (e) drying moulds and cores.

Proposed Test for Adherence of Enamel to Cast Iron. W. C. Cress and H. G. Fisk. (Bulletin of the American Ceramic Society, 1944, vol. 23,

Mar. 15, pp. 123–125). The important physical characteristics influencing the adherence of enamel to cast iron are reviewed and a technique for testing the adherence is described. Enamels on cast iron are normally under a small compressive stress, and by progressively increasing this stress until the enamel flies off, the relative adherence of the enamel to the iron can be measured. The results obtained using this principle were reproducible within fairly close limits.

PROPERTIES AND TESTS

(Continued from pp. 52 A–58 A)

Testing Steel. H. Brearley. (Engineer, 1944, vol. 177, June 9, pp. 438–440 ; June 16, pp. 458–459). The tensile test was originally developed for wrought iron, and it is shown that the information it gives in reference to wrought iron is not the same as that when it is applied to steel. The usefulness of the Brinell hardness test and the Izod impact test rather than the tensile test for steel is pointed out. The effect of hot-working on the results of Izod tests in which the bars are fractured across the length and along the length are discussed in detail. The regular use of tests of the latter type would reveal to both makers and users that there are amazing differences between steels now regarded as alike.

Metals and Alloys Comparison Charts. E. Engel. (Iron Age, 1944, vol. 153, Mar. 30, pp. 51–53). A series of charts is presented in which the costs and properties of the principal non-ferrous metals are compared with those of 18/8 stainless steel, mild steel and grey iron.

The Increasing Importance of the Bessemer Process. S. J. Creswell. (Yearbook of the American Iron and Steel Institute, 1943, pp. 162–182). The improved control of blast-furnace practice, dephosphorising and of converter blowing has made it possible to improve the uniformity of the properties of Bessemer steel, the production of which is increasing in the United States. The properties of open-hearth and acid-Bessemer steels are compared. The influence of nitrogen on the physical properties of Bessemer steel are still the subject of research. It is certain, however, that nitrogen and phosphorus together are largely responsible for the differences in properties between the two types of steel.

The Notched Bar Impact Test. J. H. Hollomon. (American Institute of Mining and Metallurgical Engineers : Technical Publication No. 1667, Metals Technology, 1944, vol. 11, Apr.). The stress distribution at the base of the notch in the notched-bar impact test is discussed and the results of impact tests and of tensile tests at low temperatures and high rates of strain are examined and correlated. Increasing the width of a notched-bar specimen in general increases the volume of material suffering deformation, and thus increases the energy required for fracture. If the ratio of notch radius to bar width is less than about 0·1, the primary effect of changing the width of the bar is to change the volume of material undergoing deformation. If, however, the above ratio is greater than 0·1, changes in the bar width will produce changes in the transverse constraint sufficient to affect appreciably the temperature of brittle failure, and will also change the volume of the material suffering deformation. Increasing the notch radius decreases the rate of strain. Lowering the temperature has the same effect as raising the rate of strain, and either measure decreases the difference between the yield strength and the fracture strength of the undeformed metal. Steels that break with a non-brittle fracture in the impact test also maintain their ductility in simple tension at low temperatures and at very high rates of strain.

Cold Reduced Strip Steel. P. J. McKimm. (Steel, 1944, vol. 114, Apr. 3, pp. 132–134, 170). Factors affecting the properties of cold-reduced steel strip are discussed. In some cases the roll surfaces are shot-blasted to roughen them, so as to produce a rough surface on the strip ; this enables higher annealing temperatures to be used without the pieces sticking together, and it improves the adhesion of paint, lacquer and other coatings. Curves are presented showing the changes in tensile strength and hardness of low-carbon steel strip for increasing degrees of cold reduction.

The Use of Electrical Resistance Strain Gauges. S. F. Dorey. (Institution of Naval Architects : Engineering, 1944, vol. 157, May 26, pp. 418–420). The wire-wound electrical resistance strain gauge in its modern form consists of a coil of wire about 0·001 in. in dia. wound on a flat former and bonded under heat and pressure between layers of resin-impregnated insulating paper, the whole being only about 0·005 in. thick. This gauge, when cemented to the surface of a stressed material with a suitable adhesive, is capable of registering minute changes of strain, both in tension and in compression, by corresponding changes in the electrical resistance of the wire. Some applications of this type of gauge by the Research Department of Lloyd's Register of Shipping for determining stresses in fireboxes and boiler drums are described.

New Developments in Strain Measurements. C. O. Dohrenwend. (Journal of the Western Society of Engineers, 1944, vol. 49, Mar., pp. 3–14). The disadvantages of mechanical strain gauges are pointed out and the principles of the electrical resistance strain gauge are explained. Three types of circuit used for these electric strain gauges are described in detail. The type used depends on the application. The first is for static measurements ; the second is for dynamic strains which vary at up to 200 cycles per sec., and the third is for strains varying at from 200 up to several thousand cycles per second. A classified bibliography with 64 references is appended.

Wire Ropes for General Engineering Purposes. N. Whincup. (Engineer, 1944, vol. 177, May 26, pp. 405–406 ; June 2, pp. 426–427). The composition of the steel for wire ropes, their construction and properties, and the design of pulley sheaves in relation to the rope diameter are discussed.

A Study of Quenched Gray Cast Irons. Microstructure and Hardness. E. Jimeno and A. Modolell. (Transactions of the American Foundrymen's Association, 1944, vol. 51, June, pp. 897–925). Experiments are reported in which the effect of the quenching treatment on the hardness and microstructure of four grey cast irons containing silicon 1·04%, 1·52%, 1·94% and 2·59%, respectively, was studied. The effect of quenching was more pronounced the longer the specimens were held at the quenching temperature. Holding at 800° C. for 1 hr. was sufficient to harden the first three of the above irons. Heating to 850° C. and quenching were necessary to harden the fourth iron. Holding at still higher temperatures before quenching led to irregular results and sometimes caused quench-cracks to form. Heating for 2 hr. at 850° C. and quenching resulted in a completely martensitic structure ; heating for 4 hr. at 850° C. and for 2 hr. at 900° C. each resulted in austenite plus martensite being formed. Numerous micrographs of the structures obtained are presented.

The Application of Hardenability Tests to Carburizing Steels. O. W. McMullan. (Industrial Heating, 1944, vol. 11, Mar., pp. 351–360). The manner in which the case depth of a case-hardened bar affects the failure of the bar under bending stresses is discussed, and it is shown that the core will probably fail before the case in large parts and the case before the core in small parts. The Jominy end-quench test is considered to be the most useful hardenability test yet devised.

Determination of Wear by Surface Measurement. G. Schlesinger. (Machinery, 1944, vol. 64, June 8, pp. 626–630). An investigation of the wear of aero-engine cylinder liners during the running-in period is reported. A "Talysurf" surface-meter was used to obtain pen records of the surface profiles before and after use.

Report of Steel Division Committee on Magnetic Tests. (Transactions of the American Foundrymen's Association, 1944, vol. 51, June, pp. 975–979). The Committee on Magnetic Powder Tests appointed by the American Foundrymen's Association report the results of a questionnaire of eight questions on magnetic powder testing to which 67 replies were received from American foundries. Thirty-one of the foundries had the equipment for making such tests, and thirty-two foundries stated that their customers applied this form of test to the castings they received.

Iron-Silicon Alloys of High Initial Permeability Due to Special Metallurgical Treatment. F. Pawlek. (Iron and Steel Institute, 1944, Translation Series, No. 179). An English translation is presented of a paper which appeared in Archiv für das Eisenhüttenwesen, 1943, vol. 16, Mar., pp. 363–366 (see Journ. I. and S.I., 1943, No. II., p. 128 A).

Fatigue Diagrams for Steels at High Temperatures. M. Hempel and H. Krug. (Archiv für das Eisenhüttenwesen, 1943, vol. 16, Jan., pp. 261–268). Fatigue curves were constructed from tests at up to 500° C. on three heat-resisting steels (a chromium-molybdenum steel, a 13%-chromium steel and a 0·51%-molybdenum steel). The machine used was a hydraulic pulsator which permitted the free elongation of the specimen during application of the load to be measured. The elongation was measured optically at 200 and at 400 magnifications. At temperatures above 300–400° C. the Wöhler method was not satisfactory because of the non-uniform elongation. For this reason the results were evaluated from the maximum elongation rates and the permanent elongation. In this way two different limits to the fatigue diagram for each steel were found. These limits enclose a region in which the elongation rate or the permanent deformation lie within permissible limits. The testing of the steels in question led to three characteristic limiting cases having fundamental differences in the shape of the fatigue curves. The suitability of a steel to withstand alternating stresses at high temperatures should be judged from both short-time static tests and the elongation in tensile-fatigue tests.

The Relationship between Load and Rate of Elongation in Creep Tests. F. Sauerwald. (Archiv für das Eisenhüttenwesen, 1943, vol. 16, Jan., pp. 269–272). The curves for the stress/elongation-rate relationship for various metals are discussed, with special reference to the position of the knee when logarithmic scales are used. There is a distinct knee in the curves for the most important metals, such as steel, lead, aluminium, magnesium, copper and tin, the position of which is a measure of the creep strength. The branch of the curve for the higher elongation rates supplies evidence of the marked influence of temperature and composition in the case of steel. The occurrence of the knee is particularly associated with the fact that at low stress a distributed flow is prevented by the polycrystalline structure and the work-hardening. Reference is made to the importance of the supplementary effect of precipitation on creep.

Creep Properties of Steels Utilized in High-Pressure and High-Temperature Superheater and Steam Pipe Practice. Part I. Carbon Steels. H. J. Tapsell. (Report J/T 134 of the British Electrical and Allied Industries Research Association: Proceedings of the Institution of Mechanical Engineers, 1944, vol. 151, pp. 54–62). Creep tests are reported on carbon steels used in superheater headers, superheater tubes and steam pipes for service at temperatures up to about 480° C. The object was to obtain data for the estimation of the stress-temperature relationships for specific

creep strains of 0·1–0·5% to occur in 100,000 hr., and these were obtained with sufficient precision to warrant their acceptance for practical purposes.

Gas Turbines. (Iron and Steel, 1944, vol. 17, May, pp. 365–366). Data are presented on the properties of alloy steels suitable for high-temperature service in gas turbines. These are classified in two groups, one for use at temperatures up to 550° C., and the other for higher temperatures. The first group includes steels containing 0·75–1·0% of molybdenum and up to 1·5% of chromium, and steels containing 7–15% of chromium with or without marked quantities of silicon. In the second group are the steels containing 18% min. of chromium and 8% min. of nickel.

Trends in Alloy Steels. J. Mitchell. (Yearbook of the American Iron and Steel Institute, 1943, pp. 230–270). The steps taken in the United States to conserve alloying elements while ensuring an adequate supply of alloy steels for war purposes are reviewed. The tendency has been towards the production of nickel-chromium-molybdenum steels of the NE 9400 series containing manganese 0·80–1·50%, silicon 0·40–0·60%, nickel 0·20–0·50%, chromium 0·20–0·40%, molybdenum 0·08–0·15% and carbon according to requirements.

Hand Hammers. R. T. Rolfe and J. R. Bryant. (Iron and Steel, 1944, vol. 17, May, pp. 379–382). The manufacture of hand hammer heads of 0·45–0·65% carbon steel is discussed with particular reference to the heat treatment. Descriptions are given of some types of failure by cracking and fracture of hand hammers in service.

METALLOGRAPHY AND CONSTITUTION

Metallurgical Research. C. S. Parsons and H. H. Fairfield. (Canadian Institute of Mining and Metallurgy : Canadian Metals and Metallurgical Industries, 1944, vol. 7, Apr., pp. 22–29). Additional facilities for metallurgical research were required by the Bureau of Mines, Ottawa, to cope with the large volume of work in hand. New physical metallurgy laboratories were erected at Ottawa on a site adjoining the existing building. A description of the new laboratories, their equipment and some of the work done is given.

Steel Plant Laboratories. (Canadian Metals and Metallurgical Industries, 1944, vol. 7, Mar., pp. 24–26). A brief illustrated description is given of the modern chemical and metallurgical laboratories of the Canadian steel-producing firm Atlas Steels, Ltd.

Some Problems in Organizing Industrial Research. W. M. Peirce. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1726 : Metals Technology, 1944, vol. 11, Apr.). The units and facilities from which a research organisation is assembled and the patterns by which it can be formed into a coherent department are discussed.

High-Fidelity Photomicrography. J. Winning. (Iron and Steel, 1944, vol. 17, May, pp. 348–350). The optical systems of the metallurgical microscope and of the illuminating apparatus and means of securing accurate light control are explained.

Industrial Radiography. V. E. Pullin. (North-East Coast Institution of Engineers and Shipbuilders : Iron and Coal Trades Review, 1944, vol. 148, June 2, pp. 829–831). Recommendations on the application of radiography for the examination of welds are made. It is essential that the interpreter of the radiographs should have a thorough and intimate

knowledge of welding so that he can not only distinguish between holes, cracks and slag inclusions, but can also indicate the probable cause of the defect.

Radiographic Inspection of Metals. R. Taylor. (Steel, 1944, vol. 114, Apr. 3, pp. 122–124, 166–170). The principles of the application of X-rays for the examination of metals and the inspection of welds are explained.

Radium Radiography in Industry. R. Taylor. (Steel, 1944, vol. 114, Apr. 10, pp. 108–112). Gamma-ray radiography and some of its industrial applications are briefly described.

Exposure Graphs for Radium Radiography of Steel. A. Morrison and E. M. Nodwell. (A.S.T.M. Bulletin, 1944, Mar., pp. 25–29). Many types of films for radiography are now obtainable, but the characteristics of some of them are not known. The results of tests to determine the relationships between gamma-ray exposure, thickness of steel and film density for each of several types of film are reported.

Radium Radiography of Thin Steel Sections. A. Morrison and E. M. Nodwell. (A.S.T.M. Bulletin, 1944, Mar., pp. 29–30). The use of radium for the radiography of steel and bronze has been limited to sections of 1 in. or more in thickness for various reasons, but with the new high-contrast, fine-grain films now available it was considered desirable to ascertain the penetrameter sensitivity for $\frac{1}{2}$-in. steel, since cases occur where X-ray apparatus is not available, and where gamma-ray radiography could be used if the desired sensitivity were obtainable. The results of penetrameter sensitivity tests using various Kodak, du Pont and Agfa films are presented. It is shown that radium radiography can be successfully used for steel down to $\frac{1}{2}$ in. in thickness.

Use of Film to Measure Exposure to Gamma Rays. A Morrison and E. M. Nodwell. (A.S.T.M. Bulletin, 1944, Mar., pp. 31–32). As an aid to establishing and maintaining safe working conditions in X-ray laboratories, a method of measuring the exposure received at any point, or by any person, over a period of time is needed. X-ray film can be used for this purpose provided that the limitations and the necessary precautions are understood. A method of determining the relationship between the amount of radiation received by a film and the blackening of the film thus produced and its application to determine whether safe conditions exist in a laboratory are explained.

Fracture and Comminution of Brittle Solids. E. F. Poncelet. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1684 : Metals Technology, 1944, vol. 11, Apr.). Experiments are described in which samples of plate glass were crushed in a special apparatus by which pressure was applied to jaws bearing on opposite edges of the glass sample. The propagation of cracks and the stress distribution in the glass was studied by photographs using a '' Microflash '' unit, which produced a light flash of great intensity lasting only one-millionth of a second. From the observations made a theory for the progression of the comminution of brittle solids is developed.

CORROSION OF IRON AND STEEL

Filiform Underfilm Corrosion of Lacquered Steel Surfaces. C. F. Sharman. (Nature, 1944, vol. 153, May 20, pp. 621–622). The spread of corrosion of steel plate surfaces coated with transparent oil-modified

synthetic lacquers in atmospheres containing acetic acid and water vapour is described. The production and growth of the hair-like corrosion tracks known as "underfilm corrosion" were observed under the microscope. The area of metal exposed by razor-blade cuts through the lacquer was quickly covered with a layer of red oxide, and radial corrosion started at points along the edges of the cuts and spread out under the film. In some cases when two of these semicircular areas intersected forming a cusp, a new type of "filiform" corrosion was set up which penetrated under the film at the relatively high speed of about 1 in. per month. The tracks varied in thickness between 0·1 and 0·5 mm., but each was practically constant throughout its length. The growth of the head of the tracks is described in detail. Tracks were observed with a length several hundred times their own width and still growing with no apparent decrease in vigour. It is suggested that the acetic acid is propelled forward undiminished in amount within the bubble as if by a sort of pumping action due to the advance of the V-shaped membrane forming the sides of the cusp.

Passivity in Copper-Nickel and Molybdenum-Nickel-Iron Alloys. H. H. Uhlig. (Electrochemical Society, Apr., 1944, Preprint No. 85–20). Passivity in an alloy appears at a critical composition which for ferrous alloys and copper-nickel alloys is related to the tendency of the d band of electronic energy states to fill with electrons. From magnetic and specific-heat data it is known that the d band of copper-nickel is filled at 60 atomic-% of copper or 40 atomic-% of nickel. Corrosion data show that transition from passivity to activity occurs at this same nickel content. Conditions of electron transfer or sharing which are described for passivity in binary combinations are essentially retained in the ternary system of molybdenum-nickel-iron alloys. It is shown that passivity in these ternary alloys, according to corrosion data for the series containing 28%, 35% and 60% of nickel in sulphuric acid occurs approximately at the predicted atomic molybdenum/iron ratio of 0·2. Molybdenum apparently can passivate either nickel or iron or both. The successful correlation of electron configurations of atoms and that of theories of the metallic state with corrosion behaviour suggests a new approach to the general problem of passivity in metals and in alloys.

Prevention of Corrosion in Steel Houses. U. R. Evans. (Engineering, 1944, vol. 157, May 26, p. 414). Various methods of preparing the surface of steel for painting with a view to protecting steel houses from corrosion are discussed. These include pickling, sand-blasting and wire-brushing. Seven-year tests have shown that the spraying of a previously sand-blasted steel surface with aluminium followed by application of a cheap paint affords admirable protection. This not only prevents corrosion for long periods, but preserves the colour of the paint for a longer time than in the case of paint applied directly to steel.

The Effect of Specimen Position on Atmospheric Corrosion Testing of Steel. C. P. Larrabee. (Electrochemical Society, Apr., 1944, Preprint No. 85–8). Many methods of exposing atmospheric corrosion test specimens are described. Steel specimens, when mounted on racks at 30° to the horizontal, corrode less on the surface exposed to the sky than on the side towards the ground. In applications such as roofing, where the underside of the sheet is not exposed, the life of the sheet may be two or three times that indicated by tests in which both sides are exposed.

BOOK NOTICE

UNDERWOOD, L. R.   "*Roll Neck Bearings.*"   Pt. 1.   "*Design, Construction and Operation.*"   A Report to the Rolling Mill Research Sub-Committee and the Rolling Mill Committee of the Iron and Steel Industrial Research Council.   8vo.   Pp.   xii + 220.   Illustrated.   London, 1943 : Iron and Steel Industrial Research Council.

This volume consists of a survey of the present position regarding the design, construction and operation of roll-neck bearings in both the ferrous and non-ferrous industries.   It contains a very comprehensive review of published literature, with bibliography, and embodies the results of discussions with manufacturers and users.   It is to be followed by a second volume giving operational data representative of British practice.

The volume is divided into sections covering all the various types of bearing in use, with excellent illustrations, a brief account of the economic and technical considerations governing selection and design, and two sections dealing with bearing metals and the theory of lubrication.   The information contained under the last two headings, as well as being of direct interest to those engaged in the rolling-mill industry, is applicable to many other branches of mechanical engineering, and should be valuable to engineering students.   The research worker in the general field of lubrication and bearings may also find this information useful for reference purposes.

The author discusses the factors involved in the theory of design of bearings, but concludes that these are much too complex to be of practical use.   He recommends, as a basis for design of fluid-film bearings (which should be the aim of every designer), the use of a minimum value for ZN/P (where Z is the oil viscosity, N the rotational speed of the journal and P the specific bearing pressure) based on existing operational data.   The author is to be commended for this decision.

In the classification of bearings, the impression may be created that the fluid-film bearing is something quite distinct from a bronze, a white metal or a synthetic-resin bearing, and although the author is obviously aware that this is not the case, the reader who is not familiar with lubrication may be led to believe that the material of the bearing determines to which class it belongs rather than the operating conditions and its geometrical design.   Also, it seems unnecessary to separate the needle bearing from the ordinary roller bearing, since the difference is chiefly one of dimensions.   The sliding without rotation through the unloaded region of a bearing applies to ordinary rollers and to balls under certain conditions just as it does to needle rollers.   There are other minor criticisms which might be made, such as, (p. 25) " . . . fluid film lubrication is characterised by . . . cool running," which, in a section on general theory of lubrication, is not strictly accurate, but such points are unimportant when viewed in relation to the work as a whole, and the author is to be congratulated on the assembly and presentation of a mass of valuable information.

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REFRACTORY MATERIALS

Heat Treatment of Refractory Materials. Parts I., II., III., and IV. N. W. Taylor and S. Zerfoss. (Industrial Heating, 1942, vol. 9, Dec., pp. 1692–1698; 1943, vol. 10, Jan., pp. 104–108; Feb., pp. 258–264; Mar., pp. 408–410). In the first part of this paper methods of measuring the expansion of refractory materials and the application of the petrographic microscope and the electron microscope for studying phase changes are dealt with. The changes in the form of silica with increasing temperature are discussed in the second part. The third part is devoted to structural changes in calcium orthosilicate, monotropic inversions and the disintegration of fireclay brick by graphite. In the concluding part the mottling of silica brick and the dead-burning of magnesite are discussed.

The Disintegration of Fireclay Products by Mixtures of Carbon Monoxide and Carbon Dioxide. G. R. Rigby, H. Booth and A. T. Green. (Transactions of the British Ceramic Society, 1944, vol. 43, Apr., pp. 73–80). The action of various mixtures of carbon monoxide and carbon dioxide on four fireclay products at 450° C. is described. With mixtures containing 25% of carbon dioxide the tendency of the specimens to disintegrate is greatly decreased. Carbon dioxide in concentrations of 10% noticeably retards the deposition of carbon round the iron spots, but at 5% the tendency to disintegration is as great as, if not greater than, that with pure carbon monoxide. The results are discussed with reference to blast-furnace linings, the relation between the carbon-dioxide content of the blast-furnace gas and the method of burdening the furnace being stressed.

Arc Furnace Refractories. N. F. Dufty. (Journal of the West of Scotland Iron and Steel Institute, 1943–44, vol. 51, Part III., pp. 35–42). Information on the properties and costs of refractories for electric-arc furnaces is reviewed. Silica bricks are the almost universal choice for roof construction. Until basic bricks are made without after-contraction and the bursting tendency of the chrome-magnesite type, they cannot be considered for roof building. Sillimanite or super-duty firebricks can be used only on furnaces working intermittently and, even so, it is doubtful if they can show any economic advantages over silica. Mathematical study of roof shapes and contours is advisable, as the circular roof cannot be built on the same principles as the open-hearth furnace roof. If the furnace is small and has a low power input, e.g., a 2-ton furnace working on 85 V. and 3000 amp., silica walls will give satisfactory service. High-power, particularly high-voltage melting is favoured to-day for economic reasons, and the resulting long fierce arc brings refractory problems in its train. With silica walls, the choice lies between burning the walls and reducing the power input and, with it, the melting efficiency. Silica cannot therefore be considered for side-wall construction in a modern furnace except as an emergency repair. Metal-cased magnesite bricks have given phenomenal lives in the United States. Stabilised dolomite bricks are out of the question because they spall badly in the temperature fluctuations of the upper part of the furnace structure. Dolomite bricks of the semi-stable variety are most suitable because their resistance to slags and spalling is higher than that of the stable brick. The two disadvantages of this brick are inability to keep in good condition for any length of time and a slight after-contraction which causes the inner course to cave in after a period in service. A 10° slope from the vertical of the side-wall shell would eliminate any trouble from this direction and have many other

advantages. Door and tapping arches, if of small span, can be constructed of semi-stable dolomite, but if the span is fairly large, silica must be used. Magnesite has never been popular in Great Britain for furnace hearths, and only dolomite can be considered in war-time. The use of graded material is definitely an asset, but the grading should be kept slightly coarser than that recommended by the Technical Panel of the Basic Furnace Linings Committee.

Refractory Insulating Bricks as Structural Materials for Modern Annealing Furnaces. E. Senfter. (Iron and Steel Institute, 1944, Translation Series, No. 187). An English translation is presented of a paper which appeared in Archiv für das Eisenhüttenwesen, 1935, vol. 6, May, pp. 473–478 (*see* Journ. I. and S.I., 1935, No. II., p. 330).

FUEL

(Continued from pp. 70 A–71 A)

Fuel Economy in Steelworks. D. J. Bradbury. (Iron and Coal Trades Review, 1944, vol. 148, June 16, pp. 901–903). Recommendations are made for saving fuel in the firing of boilers and reheating furnaces. The method of giving instruction to furnace men and the difficulties met with in bonus schemes are discussed.

Feedwater Treatment at Weirton's High-Pressure Station. J. H. Strassburger. (Iron and Steel Engineer, 1944, vol. 21, Apr., pp. 51–58). A description is given of the boiler plant, feed-water systems and turbines at the works of the Weirton Steel Company. The boiler plant supplies steam at 800 lb. per sq. in. and at 800° F. to two 12,500-kVA. turbo-generators. The feed-water in particular is discussed. The make-up water is Ohio River water, which fluctuates rapidly in hardness, total solids and turbidity. Soda ash and lime are used in the hot process tanks for water treatment. The soda ash charge amounts to about 0·135 lb. per 1000 lb. of water and the lime charge to 0·038 lb. per 1000 lb. of water.

The Elimination of Carry-Over under Steel-Mill Operating Conditions. H. M. Rivers and W. P. Hill. (Transactions of the American Society of Mechanical Engineers, 1943, vol. 65, pp. 149–154). Measures taken at the boiler plant of the Bethlehem Steel Company to prevent the excessive carry-over of boiler-water in the steam are described (*see* Journ. I. and S.I., 1943, No. I., p. 191 A).

Symposium on Underfeed Stokers as Applied to Furnaces. (Institute of Fuel and British Coal Utilisation Research Association, March 28, 1944). At this symposium the following papers were read :

Underfeed Stokers for Firing Industrial Furnaces, by E. L. Tinley.
The Use of Coal and Coke as Fuels for Firing a Heat Treatment Furnace (Batch Type) by Means of an Underfeed Stoker, by E. L. Tinley.
Underfeed Stokers for Industrial Furnaces, by G. Wilkie.
Underfeed Stokers and Their Application to Industrial Furnaces, by C. H. Williams.
Underfeed Stokers for Firing Furnaces with Fluid Heat Transmission Systems, with Case Histories and Troubles, by B. N. Reavell.
Experiences with an Underfeed Stoker at Steelworks, by T. B. Wilson.
The Application of Underfeed Stokers to Small Reheating Furnaces, by J. E. Trickett.
The Utilisation of Fuel in the Heat Treatment of Metals, by M. H. Chantry.

Direct-Fired Air Heaters, by E. Watkinson.

Underfeed Stokers as Applied to Industrial Furnaces, by A. J. W. Black.

Underfeed Stokers for Furnaces, by H. C. Armstrong.

A summary of the above papers was published in the Journal of the Institute of Fuel, 1944, vol. 17, June, pp. 133–144.

Some Practical Aspects of Automatic Control. W. H. Steinkamp. (Industrial Heating, 1942, vol. 9, Oct., pp. 1301–1308; Nov., pp. 1466–1472; Dec., pp. 1614–1622; 1943, vol. 10, Jan., pp. 42–49, 82; Feb., pp. 180–188; Mar., pp. 344–350). The first section of this paper covers the elementary theory of automatic fuel control for industrial furnaces, particularly heat-treatment furnaces. The second and third sections deal respectively with pneumatic and electric mechanisms for fuel control. In the fourth section practical applications of automatic control to several kinds of industrial furnaces are described.

Studies of Heat Transmission through Boiler Tubing at Pressures from 500 to 3300 Pounds. W. F. Davidson, P. H. Hardie, C. G. R. Humphreys, A. A. Markson, A. R. Mumford and T. Ravese. (Transactions of the American Society of Mechanical Engineers, 1943, vol. 65, pp. 553–579). A report is presented on studies of heat transfer and pressure drop in steam-generating tubes at pressures from 500 to 3300 lb. per sq. in. and under exposure to furnace heat in large steam-generating units.

Heat-Transfer Data. E. F. Lype. (Mechanical Engineering, 1944, vol. 66, Apr., pp. 254–256). Formulæ and curves are presented to facilitate calculating the coefficient of heat transfer in the flow of gases over banks of boiler tubes for any given tube spacing, tube diameter, gas velocity and mean film temperature.

Heat Transfer and Fluid Resistances in Ljungstrom Regenerative-Type Air Preheaters. H. Karlsson and S. Holm. (Transactions of the American Society of Mechanical Engineers, 1943, vol. 65, pp. 61–71). A review of experiments and studies on the heat transfer and pressure drop in Ljungstrom regenerative air preheaters is presented. Some tests were carried out in Sweden by the Ljungstrom Steam Turbine Company, and others at the Wellsville plant of the Air Preheater Corporation.

Utilizing Pulverized Coal in the Metallurgical Industries. C. F. Herington. (Transactions of the American Society of Mechanical Engineers, 1943, vol. 65, pp. 393–400). The design of pulverised-coal-fired furnaces for melting iron, for forge shops and for rolling mills is discussed with numerous drawings. Attention is drawn particularly to burner design and coal distribution systems, including pneumatic transport.

Pulverized Coal for Forge Furnaces. R. B. Engdahl and F. E. Graves. (Transactions of the American Society of Mechanical Engineers, 1943, vol. 65, pp. 31–41). *See* Journ. I. and S.I., 1943, No. I., p. 192 A.

Progress in Air Cleaning of Coal. D. R. Mitchell. (Transactions of the American Institute of Mining and Metallurgical Engineers, 1942, vol. 149, pp. 116–137). Descriptions are given of processes and equipment for the dry cleaning of coal by currents of air.

Control of Solids in a Closed Washery Water System. J. A. Younkins, C. P. Proctor and E. D. Hummer. (Transactions of the American Institute of Mining and Metallurgical Engineers, 1942, vol. 149, pp. 138–145). The removal of solids from a closed water system for coal washing by a method of selective settling is described.

A New Graphic Presentation of Coal-Cleaning Characteristics. G. A. Vissac. (Transactions of the American Institute of Mining and Metallurgical Engineers, 1942, vol. 149, pp. 146–157). A method of constructing coal " washability " curves is described.

Carbonizing Properties and Petrographic Composition of Thick Freeport-Bed Coal from Harmar Mine, Harmarville, Allegheny County, Pa., and the Effect of Blending this Coal with Pocahontas No. 3 and No. 4 Bed Coals. J. D. Davis, D. A. Reynolds, G. C. Sprunk, C. R. Holmes and J. T. McCartney. (United States Bureau of Mines, 1943, Technical Paper No. 655).

Significance of Criteria of Coal Plasticity. H. H. Lowry and C. O. Junge, jun. (American Chemical Society : Industrial and Engineering Chemistry, 1944, vol. 36, Apr., pp. 308–310). In a survey of the carbonisation characteristics of American coals, the United States Bureau of Mines has reported values for the proximate analyses and plastic properties of the coals used and the physical properties of the cokes produced. In the present paper a statistical study of the data obtained from the above survey indicates that there is a marked correlation between the proximate analyses of the coals and the plasticity indices obtained with the Davis and Gieseler plastometers. It is also shown that the physical properties of the cokes produced can be calculated equally well from either plasticity indices or proximate analyses.

The By-Product Coke Oven in Defence and Industry. C. J. Ramsburg. (Transactions of the American Institute of Mining and Metallurgical Engineers, 1942, vol. 149, pp. 242–253). The importance of the coke producing industry in United States economy is reviewed and details are given of the many applications of the by-products.

Combined Gas Producer and Iron Reclamation Plant. A. G. Arend. (British Steelmaker, 1944, vol. 10, June, pp. 259–262). A brief description is given of a plant which acts in the dual capacity of furnishing gas as the chief item, and secondly, as a modified form of small blast-furnace to recover iron from open-hearth slag. Producers of this kind are for a large gas supply, and can only be used where there is a huge demand, since there would not otherwise be sufficient ash from the coke to fuse the open-hearth slag in the charge. This charge is prepared by passing coke (75%) and slag (25%) through a mixing plant and up an inclined hoist to the top charging bell of the producer. Neither water, steam, nor aqueous vapour of any kind is injected into this type of producer, which has the usual cylindrical brick-lined shaft. The bottom is, however, specially shaped to accommodate tuyeres and holes for tapping the slag and iron. The large size of this type of producer consumes about 300 tons of lump coke per 24 hr. and is served by one attendant. In the ordinary way hot producer ash is lost as so much waste, but in these producers it is put to profitable use to recover iron from open-hearth slag.

Gas Washing Developments. H. O. Johnson. (Eastern States Blast Furnace and Coke Oven Association : Blast Furnace and Steel Plant, 1944, vol. 32, Apr., pp. 46 S–50 S). A description is given of the Brassert three-stage gas washer installed in 1941 by the American Steel and Wire Company. The washer is designed to clean 18,000 cu. ft. of gas per min. for three stoves, two being on gas at a time. The cleaned gas has an average dust content of 0·025 grain per cu. ft. with inlet and outlet gas pressures of 33 and 11 in. of water respectively.

PRODUCTION OF IRON

Reducibility of Oxides and Sulphides in Metallurgical Processes. H. J. T. Ellingham. (Journal of the Society of Chemical Industry, 1944, vol. 63,

May, pp. 125–133). From data which have recently become available, diagrams have been prepared showing the variation with temperature of the standard free energies of formation of the oxides and sulphides of metals and of certain non-metals commonly used in metallurgical reduction processes. A method of representation has been devised which makes it possible to read off directly from the diagrams the relative tendencies of the elements to combine with oxygen or with sulphur, or to displace one another from their oxides or sulphides under various conditions of temperature and pressure.

Blast Furnace and Raw Materials Committee, Proceedings. (American Institute of Mining and Metallurgical Engineers, Blast Furnace and Raw Materials Conference, Apr. 23, 1941, vol. 1). The first Conference of the Blast Furnace and Raw Materials Committee of the Iron and Steel Division of the American Institute of Mining and Metallurgical Engineers was held at Chicago.

Four papers were presented at the first session; these were :

Correlations of Some Coke Properties with Blast-Furnace Operation, by H. W. Johnson. *See* Journ. I. and S.I., 1942, No. II., p. 7 A.

Experiences in the Use of High-MgO Slags, by M. E. Nickel. The working of a blast-furnace with a high-magnesia, low-alumina slag for the production of a low-manganese iron is described.

Failure of Blast-Furnace and Stove Shells, by G. T. Williams. The probable causes of the cracking of four blast-furnace stove shells at heights of 19, 26, 32 and 39 ft. respectively, are discussed.

Stove-Dome Temperature Control, by G. E. Steudel. Nine attempts to provide adequate protection for thermocouples in blast-furnace stoves are described. The best method of temperature measurement was found to be with a Rayotube pyrometer.

The session concluded with a discussion of some unusual experiences when blowing-in blast-furnaces.

The second session consisted of four papers, namely :

Operation of a Blast Furnace for the Production of High-Sulphur Iron, by M. M. Wheldon and G. C. Hanna. An account is given of blast-furnace practice when producing iron with a high sulphur content. Desulphurisation in the ladle with soda ash was carried out.

Desulphurization of Molten Iron with Soda Ash and Effect of Desulphurized Hot Metal on Open-Hearth Practice and Steel Quality, by C. L. Labeka and J. E. Walker. *See* Journ. I. and S.I., 1941, No. II., p. 199 A.

Effects of Scrap in the Blast-Furnace Burden, by C. L. T. Edwards. *See* Journ. I. and S.I., 1941, No. I., p. 147 A.

Temperature Gradients through Composite Carbon Columns and Their Application to Blast-Furnace Linings, by F. J. Vosburgh and M. R. Hatfield. *See* Journ. I. and S.I., 1942, No. I., p. 1 A.

Blast Furnace and Raw Materials Committee, Proceedings. (American Institute of Mining and Metallurgical Engineers, Blast Furnace and Raw Materials Conference, Apr. 16–17, 1942, vol. 2). The second Annual Conference of the Blast Furnace and Raw Materials Committee of the Iron and Steel Division of the American Institute of Mining and Metallurgical Engineers was held at Cincinnati, with P. J. Dolan as chairman. The Conference was divided into three sessions on raw materials, blast-furnace operation, and furnace design and construction, respectively.

The following papers were presented at the first session :

Size Preparation of Lake Ore, by E. W. Davis and H. H. Wade. The possibilities and problems involved in screening Lake Superior ores into several sizes and in sintering the fines are dealt with.

Types of Ores Expected Fifteen Years Hence, by C. L. Wyman. Except for the hematites of the eastern Mesabi range, which are low in alumina, more concentration of ores by water processes will be carried out, and in the lean ores the iron content will be raised and the silica content lowered until a point is reached where it is uneconomic to concentrate at the mine and concentration at the blast-furnace will begin.

Present Methods of Grading Iron Ores and Possible Means of Improving Them, by W. D. Haselton. The grading of ores at the Lake Superior mines is described with particular reference to the block system and the " Six-Run " method.

Ore Grading and Variations in Analysis at the Furnace Plant, by G. T. Williams. The method of unloading iron-ore cargoes and stockpiling the ore practised by the Youngstown Sheet and Tube Company is described.

Variations in Silica Content of Iron Ores, by R. A. Lindgren. Data on variations in the silica content of shipments of Lake Superior ores are presented and methods of improving the uniformity of analysis are discussed.

Calcination Rates and Sizing of Blast-Furnace Flux, by T. L. Joseph, H. M. Beatty and G. Bitsianes. *See* Journ. I. and S.I., 1944, No. I., p. 187 A.

Slag Control by Introduction of Flux through Blast-Furnace Tuyeres, by C. G. Hogberg. *See* Journ. I. and S.I., 1943, No. II., p. 7 A.

Some Physical Characteristics of By-Product Coke for Blast Furnaces, by C. C. Russell and M. Perch. *See* Journ. I. and S.I., 1943, No. II., p. 36 A.

Pyrometry at the Coke Oven, by R. B. Sosman. *See* p. 46 A.

The second session included the following papers :

Physical Aspects of the Dust Catcher, Gas Washer and Precipitator on No. 3 Furnace at Carrie, by C. P. Clingerman and C. J. Fleisch. *See* Journ. I. and S.I., 1943, No. II., p. 5 A.

Results Obtained from Surveys of Gas at Furnace Tops, by J. M. Stapleton. *See* Journ. I. and S.I., 1943, No. II., p. 7 A.

Carbon and Carbonaceous Hearths in Iron Blast Furnaces, by H. T. Rudolf. European practice in the preparation of blast-furnace hearths with mixtures of ground coke and tar is described.

The third session consisted of three papers, namely :

Results of Enlarging Furnaces from 20 to 25 Feet, and Probable Future Developments, by A. G. McKee. Blast-furnace dimensions are discussed with special reference to furnace-top sizes, flue-dust losses through off-take openings, the ratio of bell diameter to stockline diameter, hearth diameter, wind rate and production.

Essential Considerations in the Design of Blast Furnaces, by A. L. Foell. *See* Journ. I. and S.I., 1944, No. I., p. 186 A.

Use of the Pease-Anthony Scrubber for Primary Washing of Blast-Furnace Gas, by J. E. Eberhardt and A. H. Fosdick.

Proceedings of the Blast Furnace and Raw Materials Conference.
(American Institute of Mining and Metallurgical Engineers, Blast Furnace
and Raw Materials Conference, Apr. 29–30, 1943, vol. 3). The Third
Conference of the Blast Furnace and Raw Materials Committee of the
American Institute of Mining and Metallurgical Engineers was held at
Cleveland, Ohio, with P. F. Dolan as General Chairman.

Seven papers were presented and discussed at this Conference. The
first on the washing of Pittsburgh coking coals, by C. D. King, and the
second on concentrating iron ores, by T. B. Counselman, have already been
abstracted (see Journ. I. and S.I., 1944, No. I., pp. 41 A and 180 A). In
the third paper, A. F. Peterson reviewed the history of the Cornwall iron-
ore mines in Pennsylvania and described the methods of magnetic concen-
tration now applied, by which over 99% of the iron is recovered. B. M.
Stubblefield then gave an account, with 49 illustrations, of the manner in
which an old blast-furnace was dismantled, a new one built on a steel
girder platform some distance away and the new one moved to the site of
the old one (see Journ. I. and S.I., 1943, No. II., p. 5 A). This was followed
by a description by E. W. Trexler of the procedure adopted by the Bethlehem
Steel Company to reline a blast-furnace ; in this case the stack was being
lined at the same time as the hearth and bosh. B. J. Harlan then pre-
sented data on the operation of a blast-furnace with a 27-ft. dia. hearth
which produced 502,790 tons (of 2000 lb.) of pig iron in 1942 with a burden
of 40% of unscreened Mesabi ore, 10% of screened Mesabi ore, 30% of Old
Range ore and 20% of sinter. Finally, R. A. Lindgren discussed the effect
of screened ore and sintered ore on blast-furnace production and reviewed
W. O. Philbrook's conclusions (see Journ. I. and S.I., 1944, No. I., p. 121 A).

Effects of Scrap in the Blast-Furnace Burden. C. L. T. Edwards.
(Transactions of the American Institute of Mining and Metallurgical
Engineers, 1942, vol. 150, pp. 64–69). See Journ. I. and S.I., 1941, No. I.,
p. 147 A.

The Control of the Working of a Blast-Furnace in Practice. B. Zherebin.
(Iron and Steel Institute, 1944, Translation Series, No. 188). An English
translation is presented of a Russian paper in which the conditions pro-
moting the smooth working of blast-furnaces are discussed. The original
appeared in Stal, 1940, No. 8, pp. 7–10.

Studies on the Falling of Ferromanganese from Zestafoni Works.
N. N. Kurnakov. (Comptes Rendus (Doklady) de l'Académie des Sciences
de l'U.R.S.S., 1943, vol. 39, No. 3, pp. 106–110). When the plant at
Zestafoni, Georgia, commenced producing ferro-manganese in 1933 trouble
was experienced in that the ferro-manganese frequently disintegrated into
a brown powder. When aluminium is present in high-carbon ferro-
manganese (containing about 84% or more of manganese) it promotes the
decomposition of the binary carbides of iron and manganese, thus weaken-
ing the bond between the particles of the alloy. The ingredients of the
electric-furnace charge should contain as little alumina as possible and the
alumina in the slag should not exceed 12–13%.

The Fundamentals Necessary to Apply Powder Metallurgy. C. Hardy.
(American Society for Testing Materials, Symposium on Powder Metal-
lurgy, 1943, Mar., pp. 1–7). The theory and practice of powder metallurgy
are discussed in two sections, one dealing with the raw material and its
preparation, and the second with its application. Powders are generally
specified as all passing 100 mesh, or 200 mesh, or certain portions as
minus 200, or minus 325 mesh. A 325-mesh sieve is equivalent to 44
microns. Tests have revealed that 35–65% of the particles passing a 325-
mesh sieve are of the order of 1 micron. This proportion affects the
physical characteristics of the finished parts, and further research on the
effects of particle size distribution is necessary.

The Effect of Pressure on the Properties of Compacts. C. W. Balke. (American Society for Testing Materials, Symposium on Powder Metallurgy, 1943, Mar., pp. 11–20). The results of tests of the effect of different pressures in the range of 5–160 tons per sq. in. on the properties of compacts made from iron and steel powders are reported. Electrolytic iron powders with a very low oxygen content gave bars having a density of 7·79–7·83 when pressed at 160 tons per sq. in. A coarser powder containing much more oxygen gave bars with densities appreciably lower over the entire range of pressures. When sintered at 1400° C. the densities of the bars pressed at the lower pressures showed a substantial increase. With pressures increasing up to 80 tons per sq. in. the tensile strength of pressed bars sintered at 1100° C. for 1 hr. increased rapidly ; on increasing the pressure still further the tensile strength increased only slightly. Increasing the sintering temperature had two effects ; on the one hand it promoted more complete sintering, but on the other hand it produced large grains. The latter effect was the dominating one, so that, on balance, the effect of the higher temperature was to reduce the strength.

The Effect of Particle Size on the Shrinkage of Metal Compacts. P. R. Kalischer. (American Society for Testing Materials, Symposium on Powder Metallurgy, 1943, Mar., pp. 31–36). Experiments on the change in length with temperature of iron powder compacts are reported. It was expected that on heating a compact it would expand in a similar manner to wrought metal, but at a slower rate. This was found to be true for compacts made from powders coarser than 200 mesh, but with compacts from finer particles, a break in the expansion curve occurred at a temperature well below the A_3 point because the shrinkage of the compact was greater than the expansion due to increased temperature. The author refers to this break in the curve as the " inflection temperature." For powders of 200 to 325 mesh the inflection temperature is 790° C. ; for powders finer than 325 mesh the inflection temperature is 550° C. The thermal expansion curves for iron, nickel, cobalt and silver compacts from powders finer than 325 mesh are presented. The ascending order of the inflection temperatures for these metals is silver, iron, cobalt and nickel.

Alloy Powders. T. H. Lashar. (American Society for Testing Materials, Symposium on Powder Metallurgy, 1943, Mar., p. 41). Some possibilities in the application of ferrous and non-ferrous alloy metal powders for producing articles by powder metallurgy are outlined.

Metal Powder Friction Materials. J. F. Kuzmick. (American Society for Testing Materials, Symposium on Powder Metallurgy, 1943, Mar., pp. 44–47). The properties of the ingredients of mixed powders for making friction materials such as clutch facings and brake linings are reviewed.

The Hot Pressing of Metal Powders. W. N. Pratt. (American Society for Testing Materials, Symposium on Powder Metallurgy, 1943, Mar., pp. 49–52). The advantages of hot-pressing as compared with cold-pressing with subsequent sintering in the powder metallurgy process are discussed.

FOUNDRY PRACTICE

Science in the Foundry. H. E. Arblaster. (Proceedings of the Institute of Australian Foundrymen, 1941, vol. 2, pp. 103–119). The application of metallurgical and chemical principles to a number of foundry operations is discussed. The operations so dealt with include : Combustion of fuels ; effect of furnace atmosphere on quality of metal ; the alloying of metals ; the use of de-oxidisers and fluxes ; and the welding of cast iron.

Boron as an Accelerator of Malleable Annealing. H. A. Schwartz. (Foundry, 1944, vol. 72, Apr., pp. 129, 182). The experience gained by the National Malleable and Steel Castings Company, Cleveland, Ohio, in the use of boron to shorten the time for malleablising iron castings is related. An addition of 0·001% of boron in the form of ferro-boron to the metal leaving the cupola spout is sufficient and may reduce the malleablising time by 10%. If too much boron has been added, it causes the temper carbon near the surface of the casting to be too finely subdivided, a condition which can be detected by the microscope.

Steel Melting Practice. J. Preston. (Proceedings of the Institute of Australian Foundrymen, 1941, vol. 2, pp. 85–98). An account is given of the methods employed in a steel foundry at Melbourne to prepare liquid steel for pouring into sand moulds. Operating procedure with the side-blown converter and the electric furnace is described, special attention being paid to control of the chemical composition of the steel while in the liquid state.

Foundry Sands Investigation Report. W. Hanks. (Proceedings of the Institute of Australian Foundrymen, 1941, vol. 2, pp. 121–152). The paper consists of the report compiled by a sub-committee appointed by the Council of the Institute of Australian Foundrymen to ascertain the extent and quality of foundry sands available in the Melbourne district. Methods of examining the sands, their location and geological origin are described in detail.

Metal Patterns. W. C. Perry. (Iron and Steel, 1944, vol. 17, June, pp. 488–490). A brief description is given of the plant required and the methods of making metal patterns, core boxes, pattern plates and core dryers for producing track links for fighting vehicles.

Moulding a Large Pulp Beater Trough. W. T. Main. (Proceedings of the Institute of Australian Foundrymen, 1941, vol. 2, pp. 51–57). A description is given of the preparation of the mould for casting a number of pulp mixing troughs 16 ft. long × 8 ft. wide × 4 ft. 6 in. deep with an average wall thickness of ¾ in.

The Making of a Propeller by Means of Strickles. D. Duncan. (Proceedings of the Institute of Australian Foundrymen, 1941, vol. 2, pp. 153–157). The making of a propeller casting by means of strickles is described in detail. The saving in cost compared with the cost of a full pattern is emphasised.

Moulding a Breeches Pipe with a Skeleton Pattern and Strickles. W. Stanway. (Proceedings of the Institute of Australian Foundrymen, 1941, vol. 2, pp. 173–176). A method of preparing a mould for a breeches pipe using a skeleton pattern and strickles is described in detail.

Moulding a Large Flanged T-Piece with Strickles. C. Smith. (Proceedings of the Institute of Australian Foundrymen, 1941, vol. 2, pp. 177–179). A method is described for making the mould for a T-pipe using a frame and strickles.

Modern Foundry Practice. C. R. Day. (Proceedings of the Institute of Australian Foundrymen, 1941, vol. 2, pp. 13–24). A survey of modern foundry practice is presented with brief descriptions of moulding machines, methods of sand and mould handling, cupola practice in Great Britain and the United States, and the fettling of castings.

Screw Conveyors in Foundries. H. Schulze-Manitius. (Giesserei, 1944, vol. 31, May, pp. 75–79). The design and application of screw conveyors in foundries is discussed and some modern types are described.

Costing for the Jobbing Iron Foundry. N. E. Weekes. (Proceedings of the Institute of Australian Foundrymen, 1941, vol. 2, pp. 69–82). Details of cost accounting in a jobbing iron foundry are given with specimens of suitable forms.

The Engineer and Foundryman. W. E. Moulding. (Proceedings of the Institute of Australian Foundrymen, 1941, vol. 2, pp. 59–67). Methods of dealing with the contraction which occurs in the solidification of steel castings are described and discussed and recommendations on the maintenance of foundry equipment are made.

PRODUCTION OF STEEL

The Effect of Chrome Oxide in Basic Open Hearth Slags. C. R. Funk. (Blast Furnace and Steel Plant, 1944, vol. 32, Apr., pp. 448–454). The problems of melting steel scrap high in chromium and of developing a slag of suitable chemical and mineralogical composition for working heats of chromium steel in the open-hearth furnace are considered. The preparation of slag samples is described and the interpretation of slag fractures explained. The scrap can be fully melted by increasing the time interval between the final scrap charge and the hot-metal addition; this delay will make the heat less foamy. The problem of obtaining a workable slag can be partly solved by charging so as to keep the silicon low and adding more lime than usual; a low-silicon iron is a great help. The lime must be in solution as early as possible as slags with a lime/silica ratio of less than 1·0 will always cause trouble. If the slag tends to thicken, fluorspar and fine ore, or mill-scale should be added. No attempts should be made to produce high-carbon heats with spinel slags. The mineralogical composition of the slag is far more important than the chemical composition, and thin sections of slags should be studied with the petrographic microscope.

Filtered Water Prolongs Life of Charging Door. J. D. Knox. (Steel, 1944, vol. 114, May 1, pp. 130–132). The maintenance charges on water-cooled doors to open-hearth furnaces at a Pittsburgh steelworks were very high. River water was used for cooling and it was found that the silt in the water lodged in the metal door frames and gradually reduced the cooling efficiency. A description is given of a filter which was installed to remove particles down to 0·001 in. This led to a substantial increase in the door life.

Proceedings of the First Electric Furnace Steel Conference. (American Institute of Mining and Metallurgical Engineers, Electric Furnace Steel Conference, Oct. 1–2, 1943, vol. 1). The first Annual Conference sponsored by the Electric Furnace Steel Committee of the Iron and Steel Division of the American Institute of Mining and Metallurgical Engineers was held at Pittsburgh, with C. W. Briggs as the General Chairman.

There were seven sessions dealing with the following subjects, respectively: (a) Electric melting furnaces; (b) refractories, electrodes and raw materials; (c) the electric furnace steel industry of 1943; (d) basic melting

and oxidising; (e) refining and deoxidising; (f) acid oxidising practice; and (g) refining and deoxidation of acid steel.

In an introductory statement H. W. McQuaid described the objects of the Electric Furnace Steel Committee and its annual conferences. The following papers were then presented :

Development and Present Status of Electric Furnace Steel Industry, by R. L. Baldwin.

Development of Electric-Arc Melting Furnaces, by S. Arnold.

Recent Trends in the Mechanical Design of Electric-Arc Furnaces, by F. W. Brooke. In this paper the relative merits of top- and door-charging are discussed.

Modern Electrode Control, by J. McBroom. Details of hydraulic and electric mechanism for moving electrodes are given.

Electrical Design of Modern Arc Furnace, by C. C. Levy. Transformers, circuit-interrupting devices, protective equipment, meters and automatic electrode control are described.

Three-Phase Arc-Furnace Circuit, by N. R. Stansel.

The Modern Induction Furnace, by F. T. Chestnut. Some induction furnace installations and the centrifugal casting of gun barrels are described.

Shortcomings of Modern Electric Melting Furnaces, by H. W. McQuaid.

The second session consisted of the following papers :

General Survey of Refractories for Electric Furnaces, by R. P. Heuer.

Present-Day Refractories for the Electric Melting Furnace, by C. A. Brashares.

Modern Refractories for the Electric Melting Furnace, by E. K. Pryor.

History and Manufacture of Electric-Furnace Electrodes, by F. J. Vosburgh.

Recent Trends in Electrode Manufacture, by B. L. Bailey.

Supply and Classification of Electric-Furnace Steel Scrap, by W. W. MacMillen.

Supply, Preparation, Segregation and Classification of Scrap, by A. C. Texter.

Scrap and Raw Materials, by C. F. Staley. A good scrap charge for electric furnaces was found to consist of bloom crop ends 50%, spillings 30%, light scrap 10% and turnings 10%.

Scrap for Electric Melting Furnaces, by W. J. Reagan.

Good and Bad Scrap, by A. J. Scheid, jun. The selection of scrap should be based on the relation of the scrap analysis to that of the steel to be made, the size of the scrap, its cleanliness and the quantities available. These points are discussed separately.

Oxidizing Materials, by W. M. Farnsworth.

Trends of Slag and Oxidising Materials Used in the Acid Electric Furnace, by J. R. Small.

Melting and Oxidizing Materials in Basic Practice, by A. J. Scheid, jun.

    " **Steelmaking Alloys.**"

        The Present Situation, by F. B. Foley.

        Nickel, by T. N. Armstrong.

        Molybdenum, by C. M. Loeb, jun.

        Vanadium and Titanium, by J. Strauss.

        Aluminium, by W. Bonsack.

        Aluminium for Steelmaking, by C. E. Sims.

In the third session, H. LeRoy Whitney in a paper entitled " **Electric-Furnace Steel and the War** " described the problems which faced the United States steel industry in the present war and how the enormous demands for steel were met.

The fourth session began with a paper " **Recent Progress in Our Knowledge of Oxidizing Reactions,**" by F. T. Sisco. Descriptions of basic electric-furnace charging practice at the following steelworks were then given : Bethlehem Steel Company, Rustless Iron and Steel Corporation, Jessop Steel Company, Rotary Electric Steel Company, Timken Steel and Tube Company, and the Carnegie-Illinois Steel Corporation. The four following papers concluded the session :

Oxidizing Slags, by K. L. Fetters.
Single-Slag Heats, by E. M. Farnsworth.
Basic Castings in Present Practice, by J. Erler.
Recent Developments in Basic Steel for Castings, by F. F. Doré.

The fifth session consisted of brief open discussions on slagging practice and the removal of non-metallic impurities, and four papers entitled :

Fundamentals of Deoxidation of Basic Steel, by H. W. McQuaid.
Control of Phosphorus and Sulphur in the Basic Electric Furnace, by W. J. Reagan.
Control of Hydrogen in Electric Furnace Melting, by H. M. German.
The Addition of Alloying Metals, by W. M. Farnsworth.
The following papers were read in the course of the sixth session :
Summary of Acid Electric Practice in Melting and Oxidizing, by C. W. Briggs.
Charging for Rapid Melting in the Acid Electric Furnace, by D. F. Sawtelle.
Charging for Rapid Melting by E. Lancashire.
Charging for Rapid Melting, by J. M. Lynn.
Charging for Rapid Melting, by C. E. Akers.
Control of Power for Rapid Melting, by C. L. Richards.
Factors Influencing the Melting of Acid Electric Steel, by J. H. G. Williams.
Fast Melting Rates and their Effect on the Quality of Steel, by W. G. Conner, jun., and F. M. Van Deventer.
Quantity and Time of Addition of Ore and Roll Scale, by T. D. West.
Characteristics of the Boil, by T. N. Armstrong.
Stopping the Boil, by R. J. Wilcox.
Problems in Maintaining 100 per Cent. Operation, by C. B. Williams.

There was also open discussion in this session on minimum melting time, oxidising slags and obtaining the maximum recovery of oxidisable alloys.

The seventh session included open discussion on the control of silicon in electric-furnace steel and eight papers entitled :

Review of Deoxidation Practice and Summary of Present Practice, by C. E. Sims.
Standardization of Refining and Deoxidising Conditions, by L. B. Polen.
Refining Slags for the Acid Electric Furnace and Their Control, by J. Juppenlatz.
Iron Oxide Content of Acid Slags and Metal, by J. B. Caine.
Deoxidation with Calcium-Silicon Alloys, by W. Finster.
Deoxidation with Aluminium, by E. C. Troy.

Inclusion Types Resulting from Deoxidation, by W. Crafts.
High-Temperature Metal—Precautions and Requirements, by H. H. Blosjo.

Finally, M. E. Goerz gave a brief account of the world's largest electric-furnace steel plant recently completed at Chicago. It is owned by the Defence Plant Corporation and operated by the Republic Steel Corporation, and comprises a completely integrated plant of one 1275-tons-per-day blast-furnace, four 250-ton tilting open-hearth furnaces which supply metal to six 70-ton Héroult electric furnaces, rolling mills and all the necessary auxiliary equipment.

Industrial Electric Furnaces. Part IV. Relationships between Bath Volume, Hearth Volume and Electric Load in Electric Melting Furnaces. Part V. Electrical Equipment (other than Busses) for Industrial Electric-Arc Furnaces. V. Paschkis. (Industrial Heating, 1944, vol. 11, Apr., pp. 558–562; May, pp. 738–742; June, pp. 902–912). Continuation of a series of articles (*see* p. 80 A). In the fourth part the influence of the size and shape of the furnace, the spacing of the electrodes and the heat loss per unit of time on the melting rate and metallurgical considerations in electric-furnace steel production are considered. In the fifth part transformers, reactors, current control equipment and mechanism for moving the electrodes of steel-melting furnaces are discussed.

Furnace Atmospheres in Arc Furnaces and Their Effect on the Hydrogen and Nitrogen Contents of the Steel. L. Villner and A. Norrö. (Jernkontorets Annaler, 1944, vol. 128, No. 3, pp. 105–134). (In Swedish). A report is presented of an investigation of the changes in composition of the furnace atmosphere in the course of several heats in two basic arc furnaces, one a 14-ton furnace with Söderberg electrodes and the other a 7-ton furnace with graphite electrodes. A formula was developed for calculating the amount of nitrogen taken up by the steel, but it was found that this nitrogen content was much less than the calculated amount during the boil; the reasons for this are discussed. There was no marked absorption of nitrogen in the period between removing the first slag and preparing the refining slag in spite of the high nitrogen content of the furnace atmosphere. In the refining period a certain amount of nitrogen was absorbed by the steel, an average for 12 charges being 0.002%; the nitrogen in the slag rose steadily in this period and could reach as much as 0.15%. The hydrogen content of the steel in relation to that of the furnace gases was studied in a number of heats. This revealed that the steel took up a considerable quantity of hydrogen from the moisture in the burnt lime during the building up of the furnace slag and that some of this was still present on tapping. This absorption of hydrogen could be reduced by preparing the slag first with limestone and then with burnt lime.

Oxide Impurities thrown out in the Teeming of Steel. H. Wentrup and F. W. Linder. (Stahl und Eisen, 1943, vol. 63, Dec. 2, pp. 873–880). Whilst the literature is rich in references to factors affecting the formation of inclusions in steel ingots, little has been written on the composition of non-metallic inclusions and the relationship between this composition and that of the steel. In this paper investigations of the composition of ingot scum in top- and bottom-poured ingots, the formation of scum from deoxidation products and from refractory materials, and the composition of impurities in the top of the ingot, on the walls and in the runners are reported. In particular the silica, alumina and manganous oxide contents of the scum forming on steels under different conditions of teeming are related to the steel composition and the refractories used.

FORGING, STAMPING AND DRAWING

(Continued from pp. 78 A–79 A)

Forging Die Design. J. Mueller. (Steel Processing, 1944, vol. 30, Feb., pp. 88–89 ; Apr., pp. 217–218). Continuation of a series of articles (*see* Journ. I. and S.I., 1944, No. I., p. 197 A). The design of dies for making rings and eye bolts by drop forging and of dies for making forgings with offsets at different heights is described.

Technical Problems in the Production of Small Steel Pressings. J. A. Grainger. (Ministry of Production : Sheet Metal Industries, 1944, vol. 19, Apr., pp. 677–683 ; May, pp. 837–840 ; June, pp. 1043–1048). Problems in the mass production of small steel pressings are discussed ; these include die design, lubrication, tool setting, limitations imposed by the metal and deep-drawing. The cushioning of presses with rubber and by hydraulic and pneumatic equipment is described.

Improved Hydraulic Presses for Wartime Requirements. J. H. Maude. (Transactions of the American Society of Mechanical Engineers, 1943, vol. 65, pp. 287–296). *See* Journ. I. and S.I., 1943, No. II., p. 45 A.

Manufacture of Steel Cartridge Cases. H. W. Worner. (Chemical Engineering and Mining Review, 1944, vol. 36, Feb., pp. 134–137). Development in the manufacture of steel cartridge cases in the United States is described. An account of the manufacturing procedure in use at most American factories is included.

ROLLING-MILL PRACTICE

(Continued from p. 79 A)

Relaying of Electrical Distribution Systems in Steel Mills. L. L. Fountain. (Iron and Steel Engineer, 1944, vol. 21, Apr., pp. 61–67). The application of relays to protect electric power distribution systems in steelworks is discussed.

The Calculation of Roll Pressure and Its Effect in the Cold-Straightening of Bars and Tubes. E. Bernhult. (Jernkontorets Annaler, 1944, vol. 128, No. 4, pp. 137–160). (In Swedish). By the application of bend test results formulæ are derived for calculating roll pressures in rotating two-roll straighteners for cold-straightening rods and tubes.

Effects of Temperature on Blooming Mill Production of Hot-Topped Steels. H. G. Forsyth. (Yearbook of the American Iron and Steel Institute, 1943, pp. 183–201). *See* Journ. I. and S.I., 1944, No. I., p. 16 A.

Rolling Alloy Steels in Canada on Combination 26 and 22-in. Mills. R. G. Drinnan. (Blast Furnace and Steel Plant, 1944, vol. 32, Apr., pp. 443–447). An illustrated description is given of the rolling mills of Atlas Steels, Ltd., on the banks of the Welland Canal in Canada. These consist of a 2-high 26-in. reversing mill working in conjunction with a 3-high 22-in. mill. There are twelve soaking pits and all necessary auxiliary equipment is provided, the object of the design being to have a comparatively inexpensive mill capable of rolling almost every kind of alloy steel including stainless steel from ingots varying in size from $9\frac{1}{2}$ in. square to 19 in. corrugated round.

The Vanderbijl New Plate Mill. (Engineer, 1944, vol. 177, June, p. 490). The erection of the new works of the South African Iron and Steel Industrial Corporation is dealt with, with special reference to a new four-high reversing mill stand with working rolls 38 in. in dia. and backing rolls 52 in. in dia., all 9 ft. 2 in. long, and driven by a 23,500-h.p. motor. The mill has been built complete with the necessary roller tables, plate leveller, cooling beds, cooling conveyors, plate shears, plate weigh-bridge and all accessory machines.

HEAT TREATMENT

(Continued from pp. 79 A–82 A)

The Effect of Supersonic Waves on the Surface Reactions of Metals. J. A. Hedvall. (Teknisk Tidskrift, 1944, vol. 74, May 20, pp. 625–626). (In Swedish). Experiments are described in which the rate of formation of surface reaction products was studied when specimens of copper were exposed to iodine vapour and to sulphur fumes, and specimens of iron to oxygen. An apparatus was used with which the specimens could be subjected to supersonic waves with a quartz oscillator. Curves are presented showing the marked increase in the reaction rates produced by the supersonic waves.

Gas-Fired Furnaces. R. H. Anderson, D. C. Gunn and A. L. Roberts. (Iron and Coal Trades Review, 1944, vol. 148, June 30, pp. 998–999). A new type of furnace for heating charges in the 500–1300° C. range is described. It has been developed primarily for town gas as the fuel, but it can be run on other clean fuel gases. The novel feature is that the furnace gases are withdrawn from the furnace chamber through permeable refractories into the heating chamber which is made of normal refractories, thus there is no flue leading from the combustion chamber. Experience has shown that at low furnace temperatures such as 500° C. this construction saves about 10% of the fuel, whilst at higher temperatures the saving is greater. These furnaces are suitable for heat treatment but not for direct melting.

Some Recent Heat-Treatment Plant Installations. (Metallurgia, 1944, vol. 30, May, pp. 24–32). Illustrated descriptions are given of heat-treatment plant for : (a) Gas carburising ; (b) salt-bath case-hardening ; (c) nitriding ; (d) induction hardening ; (e) bright annealing, and (f) stress-relieving large components.

The Nitriding Process. E. Simister. (Metallurgia, 1944, vol. 30, May, pp. 18–24). Some electric nitriding furnace installations and the mechanism of the process are described with details of modern nitriding steels and their heat treatment.

Decarburization Control with Nitrogen Gas Atmosphere in Alloy Steel Annealing. J. L. Kozma. (Wire and Wire Products, 1944, vol. 19, Apr., pp. 227–237, 262–264). The use of a protective atmosphere high in nitrogen for annealing alloy steel rods and coils of wire is discussed. The atmosphere is called " Monogas " and is generated by burning air and natural gas in the ratio of 9/1 in a closed chamber and purifying the products of combustion. The carbon dioxide is removed in an absorption tower by monoethanol-amine ; the bulk of the moisture is removed by a surface condenser and the remainder in an activated alumina drier. Gas equilibrium charts, tables of gas analyses and data on the amount of decarburisation for five annealing furnace charges (two N.E. nickel-chromium-molybdenum steels and three S.A.E. nickel-chromium steels) are presented and discussed.

Characteristics and Applications of Controlled Atmospheres for Heat Treating. C. E. Peck. (Steel Processing, 1944, vol. 30, Jan., pp. 50–51; Feb., pp. 111–113; Apr., pp. 241–243). Curves are presented showing the products of combustion when methane is burnt with air in air/gas ratios extending from 3/1 to 10/1, together with tables of recommended furnace atmospheres, temperatures and heating cycles for the heat treatment of steel, copper and various alloys. Methods of preparing lean and rich " endogas," " exogas," " monogas " and " ammogas " are described.

High Frequency Heating. (Machine Shop Magazine, 1944, vol. 5, May, pp. 77–82). The principles of heating by means of high-frequency currents are explained, the necessary equipment is described and some metallurgical applications are discussed. There are three broad types of equipment available, namely, rotating machines, spark-gap oscillators and valve oscillators. The first operates at frequencies of the order of 10,000 cycles per sec. This relatively low figure gives greater heat penetration below the surface of parts to be case-hardened. Spark-gap generators work at about 100,000 cycles per sec.; their use is not very extensive as their maintenance requires very careful attention. The biggest developments have taken place in valve oscillators which work at up to 100,000,000 cycles per sec.

The Heat Treatment of Steel from the Heat of Rolling. R. Schäfer and W. Drechsler. (Zeitschrift des Vereines Deutscher Ingenieure, 1944, vol. 88, Jan. 22, pp. 47–50). Procedures for the hardening and tempering of steel bars by quenching them from the temperature at which the bar leaves the last stand of the rolling-mill are discussed. The reheating of billets can be controlled so that the temperature of the bar in the last pass is between 920° and 820° C. By quenching the bar in water from this temperature and then tempering, an excellent combination of properties can be obtained. Tables of properties obtained after heat-treating a high-carbon steel and five low-alloy steels in this way are presented. The advantages of the process, which include a saving in fuel, are pointed out.

Some Developments in the Hardening of Ferrous Alloys. A. E. Shorter. (Metallurgia, 1944, vol. 30, May, pp. 33–37). A machine for the automatic flame-hardening of parts by the Shorter process is described and the results of hardness tests across sections of hammer heads hardened by this process are given.

The Hardening of Rail Ends by High-Frequency Current. V. Vologdin. (Iron and Steel Institute, 1944, Translation Series, No. 189). An English translation is presented of a paper which appeared in the Russian journal Stal, 1938, No. 8–9, pp. 47–51 (*see* Journ. I. and S.I., 1939, No. II., p. 93 A).

Handling and Conditioning Drill Bits. (Chemical Engineering and Mining Review, 1944, vol. 36, Mar. 10, pp. 159–160). The procedure for sharpening, hardening and tempering worn drill bits used in the Adirondack iron-ore mines is described.

WELDING AND CUTTING

Automatic Arc Welding. G. W. Birdsall. (Steel, 1944, vol. 114, May 1, pp. 100–103, 138–141). The sequence of processes for the mass production of the rollers which carry tank caterpillar track as it returns along the top or upper portion of its travel is described, with particular reference to automatic welding.

Flash-Butt Welding. J. H. Cooper, J. J. Riley and J. C. Barrett. (Iron Age, 1944, vol. 153, Apr. 13, pp. 60–65; Apr. 20, pp. 79–84; Apr. 27, pp. 48–54). Factors affecting the quality of flash-butt welds are discussed. The effect of high energy input for a short time is to increase the volume of molten metal at the " liquid bridges " and to leave a shallow heat-affected zone. When a low energy input is applied for a longer time the heat lost by radiation will be lower and that lost by conduction will be greater; the depth of the heat-affected zone will also be greater. Applying too much upsetting force is very detrimental to the quality of the weld as it squeezes out too much molten and plastic metal; apart from the cost of removing excessive extruded metal there is evidence that the fatigue strength of such welds is reduced.

The Effect of the Structure Obtained by Heat Treatment on the Endurance Limit of Welds in Steel St 44. C. Schaub. (Tekniska Tidskrift, 1944, vol. 74, May 20, pp. 617–623). (In Swedish). Tests are described the results of which indicated that heat treatment does not affect the endurance limit of either arc or gas welds in steel St 44 (a steel with a tensile strength of 44 kg. per sq. mm.). The endurance limit depends on the properties of the steel deposited and still more on the occurrence of gas holes or slag inclusions.

Radiology in Relation to Welding. H. Harris. (North-East Coast Institution of Engineers and Shipbuilders: Iron and Coal Trades Review, 1944, vol. 148, June 23, pp. 949–951). The principles governing the use of X-rays for examining welds are explained. In welding, the mechanical and material strengths of the joint design and the intrinsic soundness of the deposited metal are involved and it is the latter consideration which may be examined by radiography. The control of welding in the production of pressure vessels is discussed.

PROPERTIES AND TESTS

(Continued from pp. 86 A–89 A)

Effect of Wartime Developments on Future Steels. W. P. Eddy, jun. (S.A.E. Journal, 1944, vol. 52, May, pp. 169–180). Metallurgical developments during the present war in the fields of improved fatigue strength, heat treatment, steel castings, welding, use of alloying elements, hardenability, special addition agents and National Emergency steels are reviewed and the author suggests how these developments are likely to affect steel-making and processing after the war.

The Inspection of Metallic Materials. J. E. Garside. (Engineer, 1944, vol. 177, June 16, pp. 459–462; June 23, pp. 478–479; June 30, pp. 498–500). A comprehensive survey of methods of inspecting and testing metallic materials is presented. This is divided in six sections on: (1) Determination of chemical composition by physical and by chemical methods; (2) determination of mechanical properties; (3) determination of wall thickness and coating thickness; (4) detection of surface defects by immersion tests, the use of fluorescent materials and the ferrographic method; (5) detection of unsound material; and (6) determination of structure.

A Logical Approach to Metallurgical Treatment. A. C. Vivian. (Metallurgia, 1944, vol. 30, May, pp. 15–17). The limitations to the conclusions which can be drawn from the results of tensile, fatigue and impact tests are pointed out. It is suggested that the toughness of a metal be considered as the reaction in the form of work, or the energy available to oppose

fracture strain or any other degree of plastic strain. The correct measurements of the specific energies of metals and alloys would be a beginning to the consideration of basic metallurgical treatment in a logical way.

A General Survey of Steels Used in the Engineering Industry. C. W. S. Glen. (Australian Institute of Metals: Australasian Engineer, 1944, vol. 44, Apr. 6, pp. 21–25). The properties and applications of the following classes of steels are reviewed: (1) Plain carbon steels; (2) alloy tool steels; (3) alloy constructional steels; and (4) stainless and heat-resisting steels. The advantages and disadvantages of war-time emergency standard specifications are discussed.

Effect of the Tempering Temperature on the Strength Properties of Molybdenum-Free Heat-Treatable Steels. A. Krisch. (Stahl und Eisen, 1944, vol. 64, Feb. 17, pp. 105–110). The effect of the tempering temperature on the mechanical properties of two plain carbon steels and ten steels alloyed with up to 1.6% of silicon, up to 2.2% of manganese, up to 2.5% of chromium, and in four cases with up to 0.21% of vanadium, was investigated using bars 60 mm. and 30 mm. in dia. For the same tempering temperature the tensile strength of the plain carbon steels and of the manganese steels was less than that of the chromium steels. The alloy steels showed no marked superiority in elongation at fracture. The steel containing 2.5% of chromium and 0.2% of vanadium had the best notched-bar impact strength.

A Quantitative Hot Workability Test for Metals. H. K. Ihrig. (Iron Age, 1944, vol. 153, Apr. 20, pp. 86–89, 170, 172). A method of determining the hot-working properties of steel bars is described. The test bar is $\frac{9}{16}$ in. in dia. and 22 in. long. It is placed in a small electric furnace with each end projecting. One end is clamped in a chuck and the other end has a clamp on it which prevents rotation but permits expansion. The furnace can be accurately maintained at the test temperature at which the bar is held for 30 min.; the motor driving the chuck is then started together with a revolution counter which stops when the bar fractures. The number of twists of the bar before fracture is a measure of its hot-workability. Bars can be tested at a series of temperatures and the one which permits the greatest number of twists before fracture is the optimum temperature for piercing or other hot-working processes.

The Effect of Cold-Rolling on the Properties of High-Strength Steel Strip. W. Puzicha. Stahl und Eisen, 1943, vol. 63, Nov. 25, pp. 853–860; Dec. 2, pp. 880–885). A report is presented on the effect of rolling at temperatures from $-183°$ C. to $+200°$ C. on the tensile properties, deformation resistance, magnetic properties, tendency to intercrystalline corrosion, and structure of strip, 2 mm. thick, of the following steels:

	(1)	(2)	(3)	(4)	(5)	(6)
Carbon %.	0·05	0·06	0·13	0·19	0·57	0·25
Chromium %.	19·6	15·4	15·0	14·4	0·7	0·7
Nickel %.	9·1	1·4	1·1	0·22	...	...
Manganese %.		14·5	16·6	18·7	1·0	1·0
Molybdenum %.	...	...	...	...	...	0·23

The deformation resistance of the austenitic steels increased sharply with increasing reductions per pass, but this resistance could be reduced by lubrication with rape oil. The deformation resistance also increased with decreasing temperature. Steel (1) attained its maximum tensile strength by reducing it a small amount in each of a large number of passes. One chromium-manganese steel and a nitrogen-treated chromium-manganese steel attained a tensile strength of almost 190 kg. per sq. mm. The strength of these steels was much less after heavy reductions in a few passes. Steels (1), (5) and (6) attained a tensile strength of only 125–150 kg. per sq. mm.

after cold-rolling. When the austenitic steels (not nitrogen-treated) were given heavy reductions per pass, the magnetic saturation value reached a maximum and then decreased, but when reduced by small amounts per pass this value steadily increased. In the cold-rolling of the austenitic steels the magnetic transformation was markedly dependent on the temperature. There was no relationship between the phase condition as determined by magnetic saturation values and the sensitivity to intercrystalline corrosion. This sensitivity decreased with increasing deformation.

Some Mechanical Properties of Plastics and Metals under Sustained Vibrations. B. J. Lazan. (Transactions of the American Society of Mechanical Engineers, 1943, vol. 65, pp. 87–98). A new oscillatory testing machine was developed for determining the mechanical properties of materials under alternating torsional stress. The damping capacity and dynamic modulus of rigidity of both plastics and metals were evaluated with this machine. The resonance-amplification factor for the plastics tested was about one-tenth that of the metals. Sustained cyclic stress below the endurance limit increased the resonance-amplification factor of the metals tested by as much as 25%. A pronounced reduction in both the resonance-amplification factor and the dynamic modulus of elasticity occurred at impending fatigue failure in all materials tested.

Hardenability from Cast Specimens. E. S. Rowland. (Iron Age, 1944, vol. 153, May 11, pp. 61–65). To save time in the preparation of specimens for the Jominy end-quench hardenability test, the Timken Roller Bearing Company adopted the method of casting instead of forging from a billet. A split steel mould was used with a mould/specimen weight ratio of between 7 and 10. The specimens were cast to the diameter of the collar and the shank was machined to size. Some results of hardenability tests are given.

Notes on Microhardness Testing and a Description of Two New and Simple Types of Testing Equipment. E. B. Bergsman. (Jernkontorets Annaler, 1944, vol. 128, No. 3, pp. 81–104). (In Swedish). The construction of microhardness testing instruments which have previously been described in the literature are reviewed. The most suitable type for comparing metallographic structures is that based on a static indenter in conjunction with a metallographic microscope. Two designs for a new type of apparatus are submitted. They are fairly simple and therefore comparatively cheap. An ordinary Vickers diamond can be used as the indenter. If desired the same diamond can be used for ordinary and for microhardness testing. The instrument can be applied in conjunction with any metallurgical microscope with an objective directed upward, and, with minor alterations, to one with an objective directed downward. The apparatus is made to apply loads in two ranges, one from 10 to 500 g. and the other from 1 to 200 g.

The Effect of Nitrogen on the Hardening Properties of Carbon Steel. H. Kjerrman. (Jernkontorets Annaler, 1944, vol. 128, No. 5, pp. 165–173). (In Swedish). It has been observed that Bessemer steel exhibits a wide range of hardness after quenching. In this paper tests are described to ascertain how the nitrogen content of the steel affects the hardness. The results showed that if a 0·70–1·00%-carbon open-hearth steel has a nitrogen content of 0·007% min. and a fairly high aluminium content (200 g. min. per ton in the ingot mould) the hardness range is equivalent to that which a Bessemer steel normally has. It is therefore probable that the formation of aluminium nitrides is the most important factor contributing to the wide hardness range of Bessemer steels.

The Effect of Nitrogen on the Hardening Properties of Basic Open-Hearth Steel with 0·80% of Carbon. B. D. Enlund. (Jernkontorets

Annaler, 1944, vol. 128, No. 5, pp. 174–177). (In Swedish). The results of tests are reported in which the surface hardness and depth of hardness were measured on quenched 1-in. dia. bars rolled from 50-kg. ingots of basic open-hearth steel containing 0·80% of carbon. Three types of ingot were prepared : one with no additions, the second with 15 g. of aluminium added in the mould, and the third with 15 g. of aluminium and 100 g. of calcium cyanamide in the mould. The results confirmed Kjerrman's conclusion (see preceding abstract) that an increase in the nitrogen content in conjunction with a suitable amount of aluminium widens the hardness range of the steel and decreases the depth of the hardened layer.

Some Physical and Wear Characteristics of Porous-Chromium-Plated Rings. T. C. Jarrett. (S.A.E. Journal, 1944, vol. 52, May, pp. 222–224). A study was made of the effect of increasing temperature on the hardness of porous-chromium-plated cast-iron piston rings for aero-engines. The decrease in hardness was gradual on raising the temperature from 70° to 500° F. ; a sudden drop in the hardness occurred between 500° and 600° F. after which the same hardness prevailed up to 700° F. ; a second marked drop in hardness occurred between 700° and 900° F. Holding specimens at 700° F. showed that 20% of the reduction in hardness occurred within 1 hr. and no further change took place after 5 hr.

Magnetic Testing to Control Quality of Ferrous Alloy Parts. W. K. Kehoe. (General Electric Review, 1944, vol. 47, Apr., pp. 59–60). The use of the direct current magnetic residual tester and the alternating current inductance comparator in testing the magnetic characteristics of ferrous alloy parts is described.

Tessellated Stresses. Part III. F. László. (Iron and Steel Institute, 1944, this Journal, Section I). Continuation of the study of tessellated stresses (see Journ. I. and S.I., 1943, No. II., p. 137 P). The characteristic component system of tessellated stresses due to crystal anisotropy is analysed for metals with cubic, hexagonal or tetragonal lattices. The effect of tessellated stresses on thermal constants is examined. Irreversibility and hysteresis may be involved. The question of modification, i.e., reduction, of tessellated stresses and their influence on density are discussed.

Effect of Deoxidation Practice on Creep Strength of Carbon-Molybdenum Steel at 850° and 1000° F. R. F. Miller. (Transactions of the American Society of Mechanical Engineers, 1943, vol. 65, pp. 309–314). The effect of deoxidising a steel containing carbon 0·11–0·13% and molybdenum 0·5% with different amounts of aluminium on its creep strength was investigated. The steel deoxidised with 0·5 lb. of aluminium per ton had a low austenite-grain-coarsening temperature ; when 1·5 lb. of aluminium per ton was used this temperature was raised considerably. Coarse or fine ferrite grains could be produced in both steels by appropriate heat treatment. When steels with similar microstructures were compared, that with a low aluminium content had a slightly higher hardness and lower impact strength than the high-aluminium steel, and the former steel was more creep-resistant at 1000° F. under stresses less than 12,000 lb. per sq. in. than the latter. The former steel also exhibited a more pronounced decrease in creep rate with time than the latter.

Creep of Metals at Elevated Temperatures—The Hyperbolic-Sine Relation between Stress and Creep Rate. P. G. McVetty. (Transactions of the American Society of Mechanical Engineers, 1943, vol. 65, pp. 761–767). The use of the hyperbolic sine to express the relation between stress and creep rate at constant temperature is advocated. Evidence is submitted to show that the commonly used straight-line relation in the log-log plot becomes unreliable when extrapolated over a considerable range into the field of low stresses.

The Commonly-Occurring Elements in Cast Iron. W. L. Allen. (Proceedings of the Institute of Australian Foundrymen, 1941, vol. 2, pp. 27–34). The effects of carbon, silicon, manganese, sulphur and phosphorus on the properties and structure of cast iron are discussed.

Improvements in Acid Resisting Silicon Iron Alloys. J. E. Hurst. (Institution of Chemical Engineers and the Society of Chemical Industry, May, 1944, Preprint). An account is given of recent research work on the properties of high-silicon cast irons. The important considerations in determining soundness in commercial castings in this alloy are the gas content, particularly the amount of hydrogen, the carbon content and the casting temperature. With not more than 2 c.c. of hydrogen per 100 g. of alloy, a carbon content close to the eutectic value for the particular composition and a casting temperature between 1220° and 1280° C., conditions of maximum soundness and freedom from hot tears are obtained. For simple general corrosion resistance a silicon content of not less than 14·25% is desirable. Silicon-iron castings may have internal stresses ; the effect of heat treatment in reducing them has been demonstrated by experiment. The existence of the unstable carbide phase and the brittle η-phase has been encountered and the influence of heat treatment and the careful control of the silicon content in removing risks of internal stresses from these causes has been recognised.

National Emergency Steels. N. E. Woldman and R. C. Gibbons. (Steel, 1944, vol. 114, May 1, pp. 116–118, 150–151). The results of tests on the mechanical properties of heat-treated N.E. steels 8735 and 8740 are reported. These are low-alloy nickel-chromium-molybdenum steels.

Use of N.E. Types of Alloy Steels to Continue after the War. C. M. Parker. (Machinist, 1944, vol. 88, June 17, pp. 83–86). The manner in which National Emergency steels have contributed to the conservation of alloying elements in short supply is discussed and data are presented on the changes in the proportions of the principal alloying elements consumed in the alloy steel produced in the United States in 1938, 1940 and 1941. It is expected that these elements will continue to be scarce for some time after the cessation of hostilities.

Post-War Steels Should Conserve Valuable Alloying Elements. C. M. Parker. (Machinist, 1944, vol. 88, July 1, pp. 97–100). The distribution of raw materials for the principal alloying elements for steel is discussed with reference to its effect on United States economy, and a policy for the development of United States resources is outlined.

The Influence of Melting Conditions on the Physical Properties of Steel Castings. H. T. Protheroe. (Iron and Steel Institute, 1944, this Journal, Section I). This paper gives a detailed report on the mechanical-test results obtained from a number of cast steels from various sources. A critical examination of the data recorded during manufacture has been made and used in conjunction with mechanical-test results in an attempt to trace the factor or factors having the most pronounced influence on the quality of cast steel. It appears that the combined phosphorus and sulphur percentage affects the mechanical properties to a much greater extent than do other factors, such as casting temperature, &c., and the property most affected is the impact value. Unsoundness, as indicated by blow-holes or porosity, also has a pronounced effect, particularly on the ductility properties as measured by the reduction of area and elongation. Its effect on the tensile properties depends to a large extent on the actual location of the defect in the test-piece. There is an indication that the casting temperature, under controlled conditions, may have a slight effect on the mechanical properties. Its influence is so weak, however, that, unless the effect of other factors is completely eliminated, it is not noticed. The microstructures of the cast steels do not differ appreciably, and give

no indication of the mechanical properties to be expected. The differences in macrostructures, however, are quite distinctive, and an explanation for the variations is put forward. The macrostructure itself does not indicate what mechanical properties are to be expected from the steel. The influence of other factors, such as the nature and distribution of inclusions, grain size and the method of manufacture, &c., has also been considered, but cannot be definitely correlated with the mechanical properties.

CORROSION OF IRON AND STEEL

(Continued from pp. 90 A–91 A)

The Corrosion of Stressed Alloy-Steel Bars by High-Temperature Steam. H. L. Solberg, A. A. Potter, G. A. Hawkins and J. T. Agnew. (Transactions of the American Society of Mechanical Engineers, 1943, vol. 65, pp. 47–52). Apparatus was constructed and techniques developed for measuring the corrosion by steam of the following steels for high-temperature service : (a) A carbon-molybdenum steel ; (b) four chromium-molybdenum steels containing 1·25%, 2%, 7% and 9%, respectively, of chromium ; and (c) 18/8 stainless steel. Within the range of the test conditions the applied stress did not affect the corrosion caused by the steam. No intergranular attack occurred except for a small amount in a 2000-hr. test on steel (a). The resistance to corrosion increased with increasing chromium content of the steel.

Corrosion of Unstressed Specimens of Alloy Steel by Steam at Temperatures up to 1800° F. G. A. Hawkins, H. L. Solberg, J. T. Agnew and A. A. Potter. (Transactions of the American Society of Mechanical Engineers, 1943, vol. 65, pp. 301–307). The relative resistance to corrosion by steam at temperatures in the 1000–1800° F. range of a number of alloy steels was determined by tests lasting up to 1300 hr. All the steels tested except a 25/20 chromium-nickel steel and a 25/15/2 chromium-nickel-tungsten steel started to corrode rapidly at some temperature less than 1800° F. This temperature increased with increasing chromium content.

A Practical Way to Prevent Embrittlement Cracking. A. A. Berk and W. C. Schroeder. (Transactions of the American Society of Mechanical Engineers, 1943, vol. 65, pp. 701–704). Suggestions, based on the results of a great number of tests with an embrittlement detector, are made for the prevention of embrittlement of boiler steel. Sodium nitrate is relatively inexpensive compared with quebracho extract and phosphate, but sodium nitrate does not affect the character of precipitated solids and therefore does not help in preventing the formation of scale. Its usefulness has not yet been determined at pressures above 400 lb. per sq. in., whereas quebracho has been proved effective at up to 700 lb. per sq. in. The lignin compounds are inexpensive but inferior to sodium nitrate and quebracho.

Durability of Light Weight Steel Construction. Part I. Effect of Copper and Other Alloys upon the Atmospheric Corrosion of Steel. J. H. Cissel and W. E. Quinsey. (University of Michigan, June, 1942, Engineering Research Bulletin No. 30). A comprehensive survey of the literature relating to the atmospheric corrosion of light-weight steel in building construction is presented ; steel dwelling houses are not referred to.

Durability of Light Weight Steel Construction. Part II. A Study of the Service Records of Light Weight Steel Construction. J. H. Cissel and W. E. Quinsey. (University of Michigan, Nov., 1942, Engineering Research Bulletin No. 30). The literature containing reports on the condition of steelwork in dismantled buildings is reviewed.

Laboratory Evaluation of Corrosion-Inhibitive Pigments. G. D. Patterson and C. K. Sloan. (Industrial and Engineering Chemistry, Analytical Edition, 1944, vol. 16, Apr., pp. 234–238). Methods for investigating the protective value of corrosion-inhibitive pigments in maintenance paints for metal surfaces is discussed, emphasis being laid upon the degree of inhibitive action rather than film durability.

ANALYSIS

(Continued from pp. 63 A–67 A)

Photoelectric Colorimetry. E. C. Pigott. (Iron and Steel, 1944, vol. 17, Mar., pp. 285–288 ; Apr. pp. 319–322 ; May, pp. 363–364, 366). The use of photocells in quantitative metallurgical analysis is discussed and descriptions are given of the Bolton and Williams photo-electric colorimeter, the Spekker absorptiometer and the Klett-Summerson colorimeter.

Cooperative Tests for Routine Chemical Analysis of a Blast Furnace Slag. H. T. Williams. (Eastern States Blast Furnace and Coke Oven Association : Blast Furnace and Steel Plant, 1944, vol. 32, Mar., p. 358). In a paper on "falling" blast-furnace slags by T. W. Parker and J. F. Ryder (see Journ. I. and S.I., 1942, No. II., p. 21 F) a method was proposed for determining the expectancy of disintegration of cooling slag from a quantitative analysis of the slag. In the present paper the results are summarised of analyses by 32 different laboratories of small quantities taken from a single 3-kg. sample in order to show the degree of uniformity of the results obtained.

Rapid Determination of Chromium, Nickel and Manganese. R. H. Jacoby. (Foundry, 1944, vol. 72, Mar., pp. 111–112, 178). Rapid methods of determining chromium, nickel and manganese in steel using the Sheard-Sanford Photelometer are described. This apparatus simplifies spectrophotometrical procedures, as elaborate equipment for segregating a spectral band for transmission measurements is not required.

Determination of Carbon by the Low-Pressure Combustion Method. W. M. Murray, jun., and S. E. Q. Ashley. (Industrial and Engineering Chemistry, Analytical Edition, 1944, vol. 16, Apr., pp. 242–248). The apparatus for the low-pressure combustion method of determining carbon in iron and steel has been redesigned to increase the speed of manipulation. A detailed description of the equipment and its manipulation is given, together with an account of experimental studies on the method. Results are also presented for the carbon content of copper.

Determination of Carbon in Low-Carbon Steel. R. W. Gurry and Hastings Trigg. (Industrial and Engineering Chemistry, Analytical Edition, 1944, vol. 16, Apr., pp. 248–250). The results of a number of tests of the precision and accuracy of the low-pressure combustion method for the determination of carbon in steel are given.

Colorimetric Determination of Tin with Silicomolybdate. I. Baker, M. Miller and R. S. Gibbs. (Industrial and Engineering Chemistry, Analytical Edition, 1944, vol. 16, Apr., pp. 269–271). A rapid and accurate colorimetric method of determining tin in steel for concentrations ranging from 0·0005% to 0·5% is described.

Processes for the Photometric Determination of Vanadium in Tool and High-Speed Steels. G. Bogatzki. (Iron and Steel Institute, 1944, Translation Series, No. 172). An English translation is presented of a paper which appeared in Archiv für das Eisenhüttenwesen, 1939, vol. 12, May, pp. 539–542 (see Journ. I. and S.I., 1939, No. II., p. 241 A).

An Application of the Spectrograph to the Inspection of Fabricated Iron and Steel. H. F. Kincaid. (Journal of the Optical Society of·America, 1944, vol. 34, Mar., pp. 141–146). The mode of operation of the spectrographic equipment in use at the Farmall Works of the International Harvester Company is described, special emphasis being laid upon the means of obtaining results quickly and of correcting possible sources of error. The flat-surface technique has been used throughout for testing forgings, castings and bars and for control tests on the plant's four cupolas, and has given the most consistent results. Determinations of the desired elements are made in the conventional manner except for the use of a single internal standard line. Rapid conversion of the line densities to percentages is made by means of a special slide-rule. Investigations showed the size of the sample to have no effect upon the results. Large variations in the finish of the testing surface, however, were found to result in over-exposure of the film; this was corrected by altering the exposure time. Length of preburn was found to have an effect upon the line-intensity of manganese in high-sulphur specimens. Constancy was reached at 40 sec. and therefore preburn was standardised at this value. The effects of the velocity of the air blast, the humidity and the voltage of the analytical spark are also considered. The speed and economy of the method described is emphasised.

British Standard Methods for the Sampling and Analysis of Coal and Coke for Performance and Efficiency Tests on Industrial Plant. (British Standards Institution No. 735 : 1944).

The Determination of Carbon Dioxide in Coals. A. E. Beet. (Fuel in Science and Practice, 1944, vol. 23, May–June, pp. 58–60). An apparatus and procedure is described for determining the carbon dioxide content of small samples of powdered coal.

A Colorimetric Method for Determining the Water-Vapor Content in Fuel Gases, Utilizing the Evelyn Colorimeter. R. J. Pfister and D. J. Kerley. (A.S.T.M. Bulletin, 1944, Mar., pp. 17–22). A technique is described for determining moisture in fuel gases, using the Evelyn photoelectric colorimeter. The analysis requires a sample of condensate frozen out at $-70°$ C. from a measured volume of gas. The amount of gas taken for sampling should be sufficient to yield about 0·25 g. of water. The increase in weight of the absorption tube after warming and venting to the atmosphere gives, after deduction for its approximate water content, the non-aqueous diluent present in the sample.

REFRACTORY MATERIALS

Refractories—The Backbone of Industry. G. Junck. (Society of Chemical Industry of Victoria, 1943, vol. 43, May–Sept., pp. 493–516). Refractories are classified and described under the following headings : The aluminium silicate group ; the aluminous group ; the magnesia group ; the silica group ; and the zirconia group. Their manufacture, their resistance to slags and the problem of refractory insulation are also reviewed.

Availability of Indian Kyanite for Super-Refractory Manufacture. C. W. Fyfe. (Industrial Heating, 1944, vol. 11, Apr., pp. 610–612). Ample supplies of kyanite from India are now available in the United States. Mullite derived from kyanite is being increasingly used in the manufacture of best-quality refractory materials. The softening point of mullite is close to its fusion point of 3335° F. Its coefficient of expansion is only 0·0000048. It has a high refractoriness-under-load, extremely low thermal conductivity and is unaffected by either reducing or oxidising atmospheres.

High Porosity Sillimanite Bricks. F. H. Clews, N. E. Dobbins and A. T. Green. (Transactions of the British Ceramic Society, 1944, vol. 43, May, p. 81). Experiments are described which had for their object the preparation of sillimanite products of high porosity and satisfactory refractoriness-under-load at high temperatures. Test results on sillimanite-anthracite, sillimanite/china-clay/aluminium and sillimanite/paper-pulp mixes are given.

Pure Oxide Refractories. D. Kirby. (Metallurgia, 1944, vol. 30, June, pp. 65–69). Laboratory ware, such as crucibles, furnace muffles, refractory tubes, &c., made of various kinds of pure oxide refractories are described. Apparatus made of alumina, magnesia, beryllia, zirconia and thoria is dealt with.

FUEL

Symposium on Fuel Economy. (Yearbook of the Coke Oven Managers' Association, 1944, pp. 209–225). J. B. M. Mason, in opening this meeting on fuel economy, held at Durham in September, 1943, made several suggestions concerning plant surveys on steam utilisation. As a fuel-saving device, he stressed the correct placing of dampers and their controllers. G. H. Harrison made several remarks on coke-oven heating and economy in fuel-gas consumption. He emphasised the importance of keeping a check on the pressure in the collecting main, which should be kept at that figure which has been found best for the oven operation. He also recommended a standard set of instruments for use on coke-ovens. Continuing the discussion, G. E. Hall said that control of fuel-gas supply to coke-ovens was important, and made several suggestions towards the solution of the problem. He also pointed out that much heat is lost by carbonising too wet a coal.

The Planning and Design of Steam-Driven Power Stations for Iron and Steel Works. K. Schröder. (Stahl und Eisen, 1944, vol. 64, Jan. 6, pp. 2–10 ; Jan. 13, pp. 24–29). The development and efficiency of electric power stations in Germany and the United States are reviewed. Data for an ideal power station are presented, and these, with the conditions imposed by steelworks requirements, are discussed with special reference to

the heat consumption, the cost of producing electricity, the materials used in constructing a power station, and power-station layout.

The Efficient Operation of Heating Furnaces. (Federation of British Industries, 1943, Fuel Economy Monograph No. 4). This monograph was prepared as part of a programme intended to stimulate interest in the economical use of fuel. It is in seven sections, as follows : (1) The chief properties and uses of natural and prepared fuels ; (2) the efficient utilisation of the heat obtainable from the fuel ; (3) the function of the furnace and the main elements of its design ; (4) how to obtain the best possible transmission of heat to the charge ; (5) how to avoid unnecessary losses of heat ; (6) how to obtain a general idea of the efficiency of a furnace plant ; and (7) notes on auxiliary plant.

Investigation of Various Designs of Burner. K-O. Borchers. (Stahl und Eisen, 1943, vol. 63, Dec. 9, pp. 894–900 ; Dec. 16, pp. 915–917). After a review of results of tests by H. Schwiedessen and others on different gas burners for industrial furnaces, a further investigation is described in which special attention was paid to the temperature distribution in the furnace when empty and when fully loaded, and to the heat-storage capacity of the brickwork. A rectangular furnace with inside measurements $2580 \times 800 \times 800$ mm. with refractory brick walls 425 mm. thick was used. The fuel was coke-oven gas mixed with air. The following types of burner were tested : (1) A "ball" burner in which the air stream met the gas stream tangentially ; (2) a special burner in which the air could be supplied either (a) within the gas stream, or (b) through an annular space surrounding the gas stream ; and (3) a flat burner designed by the Wärmestelle, Düsseldorf. Burners (1) and (2a) were rapid-mixing burners, and were particularly suitable for forge and rolling-mill reheating furnaces. Burners (2b) and (3), the latter with the air supply below the gas, were slow-mixing burners and were recommended for lower temperature work, e.g., heat-treating. The lower waste-gas temperature when rapid-mixing burners are used can be turned to economic advantage in the heating-up period of batch furnaces.

Metallic Recuperators Increase Heating Efficiency. J. H. Loux. (Steel, 1944, vol. 114, June 12, pp. 116–118). A brief description is given of a type of metal recuperator which is being increasingly used with reheating furnaces in the Pittsburgh district. Different cast irons were tested to determine the best material to use for the elements, and an alloy cast iron known as Liesconit was decided upon ; this contains 30% of chromium, 2% of nickel and $1 \cdot 50\%$ of carbon and it is satisfactory for temperatures up to $1800°$ F. The recuperator is made of elements 4 ft. long with a head 6 in. wide $\times$ 9 in. high ; these are bolted together with an asbestos rope seal in a groove along the edge of each element. Numerous tongue-like projections are cast integral with the element on the inside and outside surfaces to assist the transfer of heat.

Utilization of Fuel Gas in War Production. R. W. Jackson. (Industrial Heating, 1944, vol. 11, May, pp. 726–736). The design of gas burners and of gas-fired equipment for a variety of applications such as heat-treating armour plate and bombs, cracking petroleum and making synthetic rubber is discussed.

Coke and the Problems Affecting its Industrial Application. G. W. Lee. (Yearbook of the Coke Oven Managers' Association, 1944, pp. 99–112). The author reviews the trends of industry in relation to fuel utilisation and endeavours to show how coke can best be applied both to well-established processes and to new developments in heat exchange.

The Efficient Working of Gas Producer Plant. (Federation of British Industries, 1943, Fuel Economy Monograph No. 3). The notes embodied in this monograph have been prepared from a practical standpoint with a

view to furnishing information and advice on the working of gas producers. The following items are dealt with in separate sections : (1) The basis of efficient gasification ; (2) the mechanism of gasification ; (3) the function of steam in the blast ; (4) evidence of inefficiency ; (5) favourable conditions for efficient gasification ; (6) fuel selection ; (7) feeding, poking, clinkering and removing ashes ; (8) controlling the blast saturation temperature ; (9) controlling the gas pressure ; (10) measuring the exit temperature ; (11) metering of coal, air, gas and steam ; (12) extent of instrumentation ; (13) checking the quality of the gas ; and (14) calculations.

The Pressure-Gasification of Solid Fuels with Oxygen. W. Offenberg. (Stahl und Eisen, 1943, vol. 63, Dec. 23, pp. 936–939). The fact that there is insufficient coke-oven gas available in Germany to meet the demand for gaseous fuel has led to investigations of other methods of obtaining gas from solid fuel. A high-pressure gasification process for brown coal and bituminous coal is described in which oxygen and superheated steam are blown into the producer at a pressure of 20–25 atm. A rich gas is produced with practically the same composition and calorific value as long-distance gas or town gas. A very high charging rate of about 750 kg. per hr. per sq. m. of hearth is required. Operating and cost data for two producers 1·2 m. in dia. are presented.

Naphthalene Washing of Coke-Oven Gas. R. H. Larke. (Yearbook of the Coke Oven Managers' Association, 1944, pp. 92–98). In recent years gas has been supplied on a large scale to public utility companies and to industrial concerns by coke-oven plants. The trouble caused by the deposition of dry naphthalene in valves and meters requires the installation of naphthalene scrubbers for its removal from the gas. The author mentions the principal types of washing plant and describes in detail the construction and operation of a "Holmes Multifilm" washer.

PRODUCTION OF IRON

DPC Blast-Furnace at Republic Cleveland. (Iron and Steel Engineer, 1944, vol. 21, Mar., pp. 85–87). A description is given of the new blast-furnace plant operated by the Republic Steel Corporation for the Defense Plant Corporation at Cleveland, Ohio. The furnace has a hearth 27 ft. in dia. with 18 tuyeres and is designed to produce 1300 tons of iron per day. The blast-furnace gas passes through a dust-catcher, a gas-washer and two electric precipitators. About 25% of the gas is used in three stoves to heat the blast ; about 1,800,000 cu. ft. per hr. are delivered to the coke-oven battery for underfiring the ovens, and the balance is used as fuel for two boilers, each capable of evaporating 150,000 lb. of water per hr. to steam at 300 lb. per sq. in. at a temperature of 700° F.

Procedure Followed in Hearth Construction. H. O. Johnson. (Eastern States Blast-Furnace and Coke Oven Association : Steel, 1944, vol. 114, May 8, pp. 120–123). A description is given of the method of constructing blast-furnace hearths adopted by the American Steel and Wire Company. The entire hearth is enclosed in a $1\frac{1}{2}$-in. steel shell-plate, 9 ft. 2 in. high and 24 ft. 7 in. in dia. Cast-iron cooling plates 6 ft. long × 5 in. thick × 5 ft. $10\frac{5}{8}$ in. wide, set with an outside radius of 11 ft. $4\frac{1}{2}$ in., are placed about 6 in. from the regular hearth cooling plates and extend the cooling zone an extra 6 ft. downwards.

Blowing-In of the World's Largest Blast-Furnace at the Zaporozhstal Works. A Ramm. (Iron and Steel Institute, 1944, Translation Series,

No. 184). This is an English translation of a paper which was published in Stal, 1938, No. 10, pp. 1–15 (*see* Journ. I. and S.I., 1939, No. II., p. 6 A).

Blast-Furnace Tap-Hole Area Cooled by Efficient Coil System. C. F. Hoffman. (Eastern States Blast-Furnace and Coke Oven Association : Steel, 1944, vol. 114, June 26, pp. 119–120). A tap-hole cooling system in use at the Sparrows Point plant of the Bethlehem Steel Company is described and illustrated. This prevents the erosion of the brickwork beneath the iron notch which occurs when cast-iron segments with cast-in pipes are employed for cooling.

Blast-Furnace Blowers Driven by Gas Turbines. (Steel, 1944, vol. 114, June 5, pp. 122–126). Data relating to the efficiency of three types of blast-furnace blower plants are presented and discussed. Each plant supplies 47,000 cu. ft. of air per min. at 17 lb. per sq. in. The first plant has a standard water-tube boiler, steam turbine, centrifugal blower and brick stove. The second plant comprises a Velox steam generator, a steam-turbine-driven centrifugal blower and a steel blast-heater ; the Velox generator has an air compressor for its combustion air driven by a gas turbine which also drives a fuel-gas compressor. The third plant consists of a gas turbine, centrifugal blowers for air and fuel gas, brick stove, starting motor and heat exchanger for the air and fuel gas. The compressor efficiencies of the three plants are 75·5%, 75·5% and 82·5%, respectively.

Centralised Lubrication for Blast-Furnaces. A. J. Jennings. (Iron and Steel Engineer, 1944, vol. 21, May, pp. 42–44, 56). A system is described and illustrated whereby the bearings on furnace tops receive lubricant under pressure from a central distributor. This centralised arrangement avoids the danger to personnel of hand lubrication and also ensures that each bearing receives the correct amount of lubricant.

Titanium Bearing Graphitized Pig Iron. (Iron Age, 1944, vol. 153, Apr. 27, pp. 47, 128). Brief details are given of the method developed by the Tonawanda Iron Corporation to prevent oxide inclusions forming in iron castings. The blast-furnace is charged with a mixture of Lake Superior ore and a titanium-bearing material such as ilmenite or rutile ; the temperature in the combustion zone is maintained as high as possible and a large volume of basic slag is used. The graphite in the iron produced is finely divided and uniformily distributed. This condition persists even after melting the pig-iron in the cupola and making the castings. It is claimed that the iron has greater fluidity, less shrinkage and better machinability.

Sponge Iron Has Definite Place in Postwar Picture. W. A. Janssen. (Steel, 1944, vol. 114, May 22, pp. 94, 145–148). The processes by which sponge iron is produced are reviewed. Several processes which have proved satisfactory in pilot plants have been unsuccessful for large-scale production. The Sieurin and Wiberg processes are exceptions and have proved very successful in Sweden. A heavy demand for sponge iron is expected after the present war, and it is suggested that instead of sintering blast-furnace flue dust, it could be directed to small direct-reduction units operating continuously and producing 1–2 tons per hr.

FOUNDRY PRACTICE

The Relationship between Blast Pressure, Blast Quantity and Cupola Dimensions. H. Jungbluth. (Archiv für das Eisenhüttenwesen, 1943, vol. 17, July–Aug., pp. 1–4). Experiments are described which enabled curves to be constructed showing the relationship between the pressure and

volume of the blast supplied to cupolas. From these and other test results a formula was derived for the blast pressure in terms of the blast volume, cupola cross-sectional area, cupola height and coke lump size.

Cost of Meehanite Castings *Versus* Welded Structures. L. F. Williams. (Iron Age, 1944, vol. 153, May 18, pp. 78–82). The manufacture of Diesel engine components is considered from the point of view of the reduced cost of Meehanite castings compared with welded parts. The finished weights, production times, finished costs and man-hours expended in producing the two types of component are compared.

Why Use Cold Blast Charcoal Iron? W. H. Melaney. (Blast Furnace and Steel Plant, 1944, vol. 32, Apr., pp. 471, 480). The belief that cold-blast charcoal iron has some undefinable property which makes it better than any other iron for casting chilled rolls is contradicted, and reasons are given for stating that hot-blast iron equally good for this purpose can be produced.

Speeding Graphitisation of Malleable Iron. C. H. Lorig. (American Foundrymen's Association : Foundry, 1944, vol. 72, May, pp. 61, 144–160). Methods of shortening the malleablising time for white cast-iron are considered from the points of view of metallurgical control and co-ordination of foundry operations.

Modern Design Marks New Steel Foundry. P. Dwyer. (Foundry, 1944, vol. 72, May, pp. 66–67, 128–130). The new plant erected at the Syming-ton-Gould Corporation, Rochester, New York, for the production of low-alloy steel castings is described. Some aspects of modern design are illustrated by photographs of the new plant.

Synthetic Sands in the Steel Foundry. H. E. Crivan. (Metal Treatment, 1944, vol. 11, Summer Issue, pp. 91–102). The enforced restriction of supplies of steel moulding sands of foreign origin have given considerable impetus to research into the merits of synthetic sands produced in Great Britain. A comprehensive survey of some of these investigations is given with special reference to the results of hot tests and the effects of milling times and ramming on the properties of the sand. Some tests are reported on moulding sands containing both oil and clay as binding materials.

Bethlehem Casts Largest Ingot Mold. (Foundry, 1944, vol. 72, May, pp. 71, 178). The casting of a corrugated one-piece ingot mould measuring 16 ft. 7 in. × 13 ft. 9 in. × 9 ft. 3 in. and weighing 200 tons recently made at the Bethlehem plant of the Bethlehem Steel Company is described and illustrated.

Casting Breech Rings for Guns. W. G. Gude. (Foundry, 1944, vol. 72, Apr., pp. 126–128, 268–270). A description is given of the technique developed by the Ohio Steel Foundry Company for making cast-steel breech rings for guns of from 57 to 240-mm. bore.

Practical Moulding Technique. R. C. Mann. (Proceedings of the Institute of Australian Foundrymen, 1941, vol. 2, pp. 1–9). Data on the contraction of steel as it cools from the pouring temperature to room temperature are presented and discussed, and the preparation of moulds for a large cast-iron cauldron and a 7-ton coke-oven charging frame is described.

Continuous Casting. V. Kondic. (Metal Industry, 1944, vol. 65, July 28, pp. 56–58). Those aspects of the rapid abstraction of heat which concern continuous casting are discussed and some effects of the rapid rate of solidification on the properties of the metals and alloys cast are dealt with.

Mechanical Handling in Foundries. (Institute of British Foundrymen : Foundry Trade Journal, 1944, vol. 73, July 13, pp. 207–213 ; July 20, pp. 233–238 ; July 27, pp. 259–261). In this comprehensive report of the Mechanical Development Sub-Committee of the Technical Committee of

the Institute of British Foundrymen, the more important methods employed in foundries for the mechanical handling of materials are surveyed.

PRODUCTION OF STEEL

(Continued from pp. 103 A–106 A)

The Danske Staalvalseværk A/S., Frederiksværk. S. Hjerdin. (Jern-kontorets Annaler, 1944, vol. 128, No. 5, pp. 178–192). (In Swedish). An illustrated description is given of the steelworks and rolling mills of the Danske Staalvalseværk A/S., at Frederiksværk about 35 miles from Copenhagen, which were completed in December, 1942. The productive capacity of the two 30-ton basic open-hearth furnaces is estimated to be 50,000 tons of ingots per annum. Heavy, medium and light rolling mills are provided which are capable of producing rounds from 8 to 100 mm. in dia., squares from 8 × 8 to 100 × 100 mm., angles from 40 × 40 to 100 × 100 mm. and sheets and plates from 3 to 25 mm. thick and up to 115 mm. wide.

Supervisory Control for the World's Most Modern Steel Mill. P. B. Garrett and M. E. Reagan. (Electrical Engineering, 1944, vol. 63, May, pp. 259–264). A description is given of the supervisory control system at the largest steelworks in the United States west of the Mississippi. This system provides for the remote control of electrical machinery by relays from one central point, thus leaving motor rooms locked and unattended except for maintenance personnel.

The Utilised Heating Surface of Checkers in the Regenerator Chambers of Open-Hearth Furnaces. K. Guthmann. (Iron and Steel Institute, 1944, Translation Series, No. 193). An English translation is presented of a paper which appeared in Stahl und Eisen, 1942, vol. 62, Sept. 10, pp. 774–779 (see Journ. I and S.I., 1943, No. I., p. 81 A).

Supplementary Heating of the Checker Chambers of Open-Hearth Furnaces. G. Prieur. (Stahl und Eisen, 1944, vol. 64, Jan. 13, pp. 21–24). A comparison is made of data on the gas consumption and steel production of a 50-ton open-hearth furnace when heated normally with coke-oven gas and when supplementary heating of the checker chambers was applied as previously described in papers by F. Engels and G. Prieur (see pp. 41 A and 42 A). An increase in production of at least 15% was noted with the same total fuel consumption.

The Removal of Nitrogen from Steel in the Basic Open-Hearth Furnace. W. Geller. (Stahl und Eisen, 1944, vol. 64, Jan. 6, pp. 10–13). Data on the removal of nitrogen from steel in basic open-hearth furnaces which were charged with hot metal from Bessemer converters are presented and discussed. When the efficiency of the nitrogen removal is taken as the ratio of the mean partial pressure in the carbon monoxide bubbles to that theoretically possible, this ratio falls rapidly as the rate of the carbon removal increases and reaches a value of about 0·2 when the carbon-removal rate is 0·25% per hr., after which it falls quite slowly. This is in good agreement with the results of H. Wentrup and W. Altpeter, who made tests on arc furnaces. With a high initial nitrogen content the efficiency is probably less than with a low one.

Control for Electric Arc Furnaces. L. V. Black. (Iron and Steel Engineer, 1944, vol. 21, May, pp. 35–41). The features of the controls now available for electric arc furnaces are explained. The advantages and disadvantages of constant- and variable-voltage furnaces are compared.

FORGING, STAMPING AND DRAWING

Forging Ferrous and Non-Ferrous Metals. R. W. Thompson. (Iron Age, 1944, vol. 153, June 8, pp. 54–57). Owing to war conditions the increased use of forgings for aircraft and other components has made necessary the purchase of forgings by contractors who previously have had little acquaintance with the processes required for their production. For the guidance of these new users the author briefly explains the different classes of forgings and describes methods for producing them.

Sixty-Millimetre Mortar-Shell Production Technique. H. M. Heckathorn. (Iron Age, 1944, vol. 153, May 25, pp. 42–44). A multi-stage, pressing technique devised by the Mullins Manufacturing Corporation, Youngstown, for the manufacture of 60-mm. mortar shells is described. Forging, machining and casting operations are avoided, so that production is rapidly increased.

" Contoured-Cavity " Forging Method Developed for Large Caliber Shells. (Industrial Heating, 1944, vol. 11, June, pp. 877–882). The sequence of processes developed by H. K. Porter Company, Incorporated, of Pittsburgh, for making large hollow shell forgings is described. An important feature of the process is that the mandrel for making the cavity is shaped to produce the contour required with a minimum of machining afterwards.

Forging Forks for Farmers. W. K. Cowdery. (Steel, 1944, vol. 114, May 8, pp. 98–99, 106). Hand and mechanical processes in the forging of ten-prong forks are described and illustrated.

Heavy Plate Sections Measuring up to 36 Feet Long Are Readily Formed on Shop-Built Press. R. L. Hartford. (Steel, 1944, vol. 114, June 12, pp. 98–99). A description is given of a press which was built up of six 500-ton hydraulic jacks equally spaced under a heavy platen and so designed as to be capable of making four bends parallel to the long sides of a plate 36 ft. long and 5 ft. wide after bending.

The Application of Electric Drives to Power Presses. G. P. F. Newlands. (Metropolitan-Vickers Gazette, 1944, vol. 20, Apr., pp. 272–280). The considerations involved in applying electric drive to power presses are discussed and some examples of such presses are illustrated. The advantage of a flywheel with special clutch arrangement on a crank-type press is pointed out and some details are given of a rotary-table high-speed automatic press.

Flame-Spinning Process. T. McElrath, jun. (Steel, 1944, vol. 114, May 29, pp. 84, 119–120). A brief description is given of a rapid process for closing tube ends. The tube is spun while multi-tip acetylene burners play on the end ; when the requisite temperature has been reached, forming tools are pressed against the hot end to shape and close it up as required. Flame-spinning has been successfully applied to tubes from $\frac{1}{2}$ to $2\frac{3}{4}$ in. in dia. The ratio of tube diameter to wall thickness should not exceed 50.

Wire Rope. G. E. Stedman. (Steel, 1944, vol. 114, May 22, pp. 104–111). The sequence of processes in the manufacture of wire rope at the works of the Union Wire Rope Corporation, Kansas City, is described and illustrated.

A.C. and D.C. Drives for Draw Benches and Wire Blocks. R. A. Geuder. (Iron and Steel Engineer, 1944, vol. 21, May, pp. 47–56). The advantages and disadvantages of various types of electrical drive for draw benches and wire blocks from the point of view of production requirements, available power supply, flexibility and first cost are considered. Many types of

electrical equipment for supplying power to draw benches are dealt with. The following types of wire-block machine are discussed : Single-head wire blocks ; single motor-driven machines of the core, core tandem, or straight tandem class ; and multiple-head continuous blocks.

ROLLING-MILL PRACTICE

(Continued from pp. 107 A–108 A)

The Reversing of Mill Trains with Current Rectifiers with Particular Reference to the Voltage Drop in the Supply Mains. G. Himmelberg. (Stahl und Eisen, 1943, vol. 63, Dec. 9, pp. 889–894). The advantages and disadvantages of using rotary transformers or current rectifiers for supplying direct current to mill motors are compared. The tests which were run at an Upper-Silesian steelworks to decide which of the two methods to employ for a heavy plate mill with rolls 3200 mm. long are described. Special attention was paid to the voltage drop in the supply mains when the mill was reversed. A decision in favour of grid-controlled current rectifiers was made.

Bloom and Billet Mills and Their Rolls. F. C. T. Daniels and D. L. Eynon. (Iron and Steel Engineer, 1944, vol. 21, May, pp. 79–91). The layout of bloom and billet mills is discussed and diagrams of several different arrangements are presented, together with details of roll calibrations for a three-high blooming-mill stand and for two three-high billet-mill stands following it.

The Modern Plate Mill. (Iron and Steel Engineer, 1944, vol. 21, Apr., pp. 18 PM–21 PM). Tables are presented giving the roll sizes, capacities and production of all the plate mills in the United States.

Recent Plate Mill Developments. R. E. Noble. (Iron and Steel Engineer, 1944, vol. 21, Apr., pp. 23 PM–46 PM). The increase in the production of steel plates in the United States between 1932 and 1943 is studied using statistics of the American Iron and Steel Institute. Developments in mill stands, mill tables, shears and other auxiliary equipment are reviewed and the layout of the plate mills of the Steel Company of Canada, the Tennessee Coal, Iron and Railroad Company, Kaiser Company Incorporated, the South African Iron and Steel Industrial Corporation, Ltd., the National Steel Company of Brazil, and of some other large mills in the United States is described.

Plate Rolling Practice. L. Bunting and T. T. Watson. (Iron and Steel Engineer, 1944, vol. 21, Apr., pp. 48 PM–51 PM, 71 PM). The plate-rolling practice at the Coatesville plant of the Lukens Steel Company is described. There are five mills at this works. These are : (1) An old three-high universal mill with rolls 74 in. long ; (2) one two-high reversing stand and one four-high stand with rolls 84 in. long ; (3) a mill completed in 1943 consisting of one roughing and one finishing stand with rolls 112 in. long ; (4) a steam-driven three-high stand with rolls 140 in. long ; and (5) a four-high steam-driven reversing mill stand with rolls 206 in. long.

Observations on Plate Mill Rolls. L. Moses. (Iron and Steel Engineer, 1944, vol. 21, Apr., pp. 54 PM–56 PM). The causes of spalling of the surface of plate-mill rolls are discussed. It was observed that spalling occurred more frequently when an unusually high proportion of light-gauge material was rolled ; this was due to the mechanical shock when cold ends entered the mill or when doubled-over "fish tails" passed between the rolls. Rolls of alloy cast iron with very finely dispersed graphite have proved to be particularly resistant to spalling.

HEAT TREATMENT

Metal-Working Tomorrow. **What's Ahead in Heat-Treating?** (Machinist, 1944, vol. 88, July 15, pp. 83–92). Possible trends in heat treatment are discussed; the significance of heat treatment becoming a continuous process by taking its place in the production line is emphasised.

New Heat-Treatment Processes for Improving Modern Steels. O. Kukla, W. Küntscher and H. Sajosch. (Stahl und Eisen, 1942, vol. 62, Dec. 17, pp. 1067–1073). Tests on the improvement in the properties of a number of steels obtained by heat-treating direct from the rolling or forging temperature are reported. The steels used included unalloyed steels with 0·16–0·52% of carbon and steels containing chromium, nickel, molybdenum and vanadium. By hardening direct from the heat of rolling and then tempering, an improvement of 2–3 mkg. per sq. cm. in the notched-bar impact values was obtained. The danger of cracking due to quenching the unevenly heated bars was dealt with by using temperature-indicating colours and withdrawing the bars from the quenching bath at temperatures between 150° and 350° C.; an intermediate annealing was not necessary. The hardening of low-carbon steels in water with no tempering was successfully developed; in this way bars 50 mm. in dia. attained a notched-bar impact strength of 8 mkg. per sq. cm. with a tensile strength of 124 kg. per sq. mm. and an elastic limit of 110 kg. per sq. mm. Another successful method of heat treatment was a high-temperature diffusion-annealing immediately after the final rolling or forging process. This prevented segregation and internal stresses without any of the detrimental effects of overheating.

The Effect of Deoxidising with Aluminium on the Depth-Hardening and Heat Treatment in Depth of Structural Alloy Steel. H. Krainer. (Archiv für das Eisenhüttenwesen, 1943, vol. 17, July–Aug., pp. 11–15). The effect of the carbon, silicon, manganese, chromium, molybdenum and aluminium contents on the hardenability of low-alloy steels was investigated. The technique developed was to heat specimens 50×20 mm., only 2–3 mm. thick, to the hardening temperature, hold them a given time, plunge them in a lead bath (held at the temperature causing the maximum austenite-pearlite transformation rate) for a predetermined time, quench in water and finally to make hardness surveys and examine the structure. The method of determining the maximum transformation rate for a steel is described. The amount of aluminium used for deoxidising the steel has a predominating effect on the hardenability. To obtain maximum hardenability in the steels investigated, which were prepared in a basic electric furnace, the aluminium addition was limited to 0·1 kg. per ton of steel.

" X " Constituent Formed in Alloy Steel on Continuous Cooling. A. R. Kommel. (Metal Progress, 1944, vol. 45, Apr., pp. 664–665). In a series of 0·5–0·6%-carbon, chromium-molybdenum cast steels, considerably more ferrite was found in the normalised than in the annealed specimens. An account of the heat treatment which produced this result is given, and the suggestion is made that the extra ferritic material in the normalised specimen is actually a constituent of the pre-eutectoid ferrite formed at isothermal transformation temperatures intermediate between those where lamellar and acicular products are formed by the transformation of austenite.

Eliminating Cracking in Heavy Forging Dies. W. Haufe. (TZ für praktische Metallbearbeitung: Iron Age, 1944, vol. 153, May 18, pp. 66–71). Cracking can easily occur in the heat treatment of heavy forging dies unless great care is exercised in preventing the temperature difference

between surface and core from becoming too great. This temperature difference is affected by the temperature of the hardening furnace, the rate at which the furnace is driven, the die size and the thermal conductivity of the die steel. Curves are presented showing: (a) The influence of the furnace temperature on the rate the die is heated; (b) the influence of die size on the heating rate; (c) the influence of die size on the above temperature difference; (d) the changes in this temperature difference with time when cooling in water, oil and air; and (e) the influence of the thermal conductivity of the die steel on the cooling rates of the die surface and core. Recommendations on the heat treatment of dies are made on the basis of the data presented.

Maximum Carbon in Carburised Cases. F. E. Harris. (Metal Progress, 1944, vol. 45, Apr., pp. 683–686). Data on the extent of the carbon film formed during carburisation of steels are briefly reviewed and the wide discrepancies between the results of different investigators are indicated. Further data are quoted to show that properly controlled furnace conditions give perfectly predictable values for the percentage of carbon at the surface and at different depths.

Gears Carburized in Electric Salt Bath Furnace at Yale and Towne Plant. H. L. Edsall. (Industrial Heating, 1944, vol. 11, May, pp. 704–714). The plant and process for carburising gears up to 12 in. in dia. for electric trucks and industrial hoists at the works of the Yale and Towne Manufacturing Company are described.

Continuous Surface Hardening of Steel by the High-Frequency Induction Method. M. G. Lozinskiy. (Iron and Steel Institute, 1944, Translation Series, No. 192). This is an English translation of a paper which was published in Vestnik Metallopromyshlennosti, 1940, No. 3, pp. 50–60 (see Journ. I. and S.I., 1941, No. II., p. 80 A).

Electrical Heat Treatment of Chromium-Molybdenum Steel Tubes. F. Vdovin. (Iron and Steel Institute, 1944, Translation Series, No. 190). An English translation is presented of an account in Stal, 1938, No. 5, pp. 48–54, of an investigation of the heat treatment of low-alloy chromium-molybdenum steel tubes at a Russian works. The tubes were 20 mm. in outside dia. and from 0·75–1·5 mm. thick. Annular copper contacts were clamped on each end and currents up to 800 amp. were passed through them. The changes in mechanical properties and microstructure after heating at different rates to different temperatures and cooling in air were investigated. Short-time electrical heat treatment at 750–800° C. gave the tubes sufficient plasticity to permit of their further cold-drawing. Varying the heating time and current strength had no effect on the mechanical properties and structure of the tubes provided that the requisite temperature was attained.

Control Equipment for Induction Melting and Heating Units. F. E. Ackley. (Industrial Heating, 1944, vol. 11, Apr., pp. 538–546, 580; May, pp. 716–724, 742). Methods of controlling low-frequency and high-frequency induction melting and heat-treatment furnaces are described.

High-Frequency Heating. A. G. Robiette. (Metal Treatment, 1944, vol. 11, Summer Issue, pp. 83–90). The fundamental principles, the metallurgical effects and the economics of three methods of high-frequency heating are considered. These involve the following equipment for generating the high-frequency current: (1) A motor coupled to a high-speed alternator to produce current frequencies of 12,000 cycles per sec.; (2) a spark gap oscillator to produce current frequencies of 50,000–200,000 cycles per sec.; and (3) a thermionic valve oscillator capable of producing a single-phase current of between 10^5 and 10^8 cycles per sec.

The Annealing of High-Carbon Steels in Protective Atmospheres without Decarburisation. W. Hülsbruch. (Archiv für das Eisenhüttenwesen,

1943, vol. 17, July–Aug., pp. 17–22). The causes of decarburisation in the annealing of high-carbon steels are reviewed and tests are described the object of which was to remove the oxygen in the scale by a preliminary treatment at 400–600° C. in a reducing atmosphere and then to anneal at 650–800° C. without decarburisation and without scale formation. Bars 3·5–4 m. long of 1·2%-carbon steel were packed in tubes 250 and 180 mm. in dia. The tubes were closed by welding, and small inlet and exit tubes for the supply of the protective atmosphere were fitted. The atmosphere was prepared by the partial combustion of long-distance gas. The large tubes were placed in a furnace and heated first to 600° C. and then to 780° C. Tables of the inlet and exit gas compositions and of the carbon content of the bars at depths up to 0·5 mm. are presented. The tests were so successful that a full-scale plant has been ordered. The bars had an excellent surface after treatment and were free from scale. If the bars were to be pickled and cold-worked it was found advantageous to oxidise the layer of reduced scale by blowing in air at 600° C.

Tool Life Increased by Improved Annealing Procedure. J. Sorenson. (Steel, 1944, vol. 114, May 8, p. 114). The effect of changing the annealing procedure for a chromium-nickel-molybdenum steel on the life of the tungsten high-speed steel used to turn it was investigated. The previous heat treatment consisted of normalising at 1600° F., heating to 1525° F., holding for 25 hr. and cooling in the furnace. The heat treatment which led to longer tool life consisted of normalising at 1650° F., heating to 1385° F. cooling to 1210° F., holding for 24 hr. and cooling in air.

Stress Relieving with a Welding Machine. R. B. Foster. (Steel, 1944, vol. 114, May 8, pp. 108–110). A method of adapting a 240-cycle A.C. motor-generator electric welding set as a source of power for induction heating to stress-relieve steel tubes is described.

The Heat Treatment of High-Speed Steel. J. F. C. Morden. (Coventry Engineering Society Journal, 1944, vol. 25, May–June, pp. 35–46). A short account is given of the development of high-speed steels since 1900, and the modern process of primary and secondary hardening is dealt with.

Improved Processing Methods Help Avoid Heat-Treat Distortion. G. W. Birdsall. (Steel, 1944, vol. 114, May 15, pp. 86–89, 134–144). The causes of the distortion of steel parts during heat treatment are analysed and methods of preventing it, including austempering and other forms of stepped quenching, are discussed.

WELDING AND CUTTING

The Application, Manufacture, Composition and Storage of Coated Metallic Arc Electrodes. O. T. Barnett. (Welding Journal, 1944, vol. 23, Apr., pp. 327–333). The applications of welding electrodes are considered in three groups, namely, those which produce fillet welds with flat, convex and concave surfaces, respectively. A detailed description is given of the sequence of processes in the manufacture of coated electrodes with information on the function of the various coating ingredients.

Hard Facing. J. R. Spence. (Welding Journal, 1944, vol. 23, Apr., pp. 318–322). The properties and applications of wear-resisting welded deposits are considered in four groups distinguished by their composition as follows : (a) Steel containing less than 20% of alloying elements ; (b) steel containing more than 20% of alloying elements ; (c) non-ferrous metals ; and (d) tungsten carbide. Charts are presented in which the following properties are compared : Hardness ; hardness plus wear ;

hardness plus wear plus heat resistance; impact test values; impact plus wear resistance; impact plus wear plus heat resistance; and grinding resistance.

Hydrogen and the Weld Cracking of Alloy Steels. G. L. Hopkin. (Metal Treatment, 1944, vol. 11, Summer Issue, pp. 125–130). The information in this paper is based on three reports, two by the author and one by the author and E. L. Evans, all issued by the Armament Research Department of the Ministry of Supply. One of these reports was on the welding of high-alloy high-tensile steels with ferritic electrodes coated with fluxes containing a controlled amount of hydrogen. Varying amounts of diffusable hydrogen can enter the heat-affected zones of welds, the amount depending on whether the weld metal is austenitic, killed ferritic or oxidised ferritic. Having regard to Zapffe's theory of hydrogen embrittlement the susceptibility to weld-cracking decreases if oxidised weld metal is deposited instead of killed ferritic weld metal, and it decreases still more if the weld metal is austenitic.

The Effect of Peening as a Method of Stress Relieving Applied to Welds. O. H. Henry and E. M. Daman. (Welding Journal, 1944, vol. 23, Apr., pp. 206-S–207-S). An investigation of the effect of changes in the rate of peening on the stress relief obtained in welds. Two plates each $12 \times 4 \times 1$ in. were beveled at $30°$ along the 12-in. sides and welded together in seven passes; they were rigidly clamped during welding and cooling. All layers except the first and last were peened at 10 blows per sec. with a round-nosed pneumatic hammer. After welding and peening, a slot 5 in. long was cut along the heat-affected zone and the distortion was measured by the increase in distance between two reference marks one on each side of the slot. The optimum rate of peening was 2 min. per ft. which reduced the distortion by $64·5\%$; peening at 5 min. per ft. reduced the distortion by $18·3\%$.

Stress-Relieving and Peening Temperatures. R. E. Spaulding. (Welding Journal, 1944, vol. 23, Apr., p. 208-S). Curves are presented showing the changes in yield strength and ultimate strength with temperature for a structural steel. From these it is deduced that the temperature at which peening should be applied to obtain the maximum stress relief is one at which the yield strength is low in relation to the ultimate strength.

A Test of Longitudinal Welded Joints in Medium and High-Tensile Steel. A. G. Bissell. (Welding Journal, 1944, vol. 23, Apr., pp. 185-S–191-S) An investigation of the tensile strength of longitudinally welded steel plate undertaken by the United States Bureau of Ships is described. Pairs of steel strip of medium and of high tensile strength were made into single specimens by welding the long edges together. It was found possible to make longitudinal welded seams in steel plate of medium tensile strength with a tensile strength equal to that of the unwelded steel, but there was some loss in ductility. In high-tensile steel the strength of the welded strips was slightly less than that of the original plate and the elongation values obtained were erratic.

Test Plugs Cut From Welds. R. V. Anderson. (Metal Progress, 1944, vol. 45, Apr., pp. 696–697). Two methods are commonly used for taking test plugs from welded joints: (a) Using an oxy-acetylene flame; and (b) trepanning the test plugs out with a form of annular saw. It is pointed out that in method (a) the steel suffers further heating changes so that the original characteristics of the weld are obliterated, and in (b) great expense is incurred by damage to the drilling and cutting equipment. A method of cutting plugs is described which eliminates this loss. Illustrations of test plugs are attached which demonstrate various weld defects.

Steel Castings—Their Properties and Use in Weldments. E. J. Wellauer. (Welding Journal, 1944, vol. 23, Apr., pp. 193-S–200-S). Comprehensive

test data on the mechanical and metallurgical properties of cast steel suitable for welding are presented and discussed.   Some specifications of castings for subsequent welding are given and the economies which can be effected by incorporating castings in welded constructions such as reduction-gear housings are pointed out.

Russian-English Dictionary of Welding Terms.   M. A. Cordovi.   (Welding Journal, 1944, vol. 23, Apr., pp. 191-S–192-S).   A list of about 250 Russian welding terms with their English equivalents is presented.

CLEANING AND PICKLING OF METALS

(Continued from p. 83 A)

An Electro-Chemical Descaling Process.   (Metallurgia, 1944, vol. 30, June, p. 76).   The Bullard-Dunn process for the electro-chemical removal of scale and oxides from ferrous metal surfaces is briefly described.

Precleaning with Solvent Emulsions.   C. S. Lowe.   (Monthly Review of the American Electroplaters' Society, 1944, Jan., pp. 29–40).   Precleaning with solvent emulsions removes solid and organic dirt which contribute to dullness on " bright " coatings and to pitting, peeling and porosity of electrolytic coatings on steel.   The total time required for cleaning is considerably reduced by precleaning with solvent emulsions.

Operation and Possibilities of Gas Pickling of Steel.   J. J. Turin.   (Iron Age, 1944, vol. 153, Apr. 20, pp. 64–70).   The operation of a gas-pickling line for steel strip is described.   The strip is passed through a preheating furnace which is a simple direct-fired tunnel with temperature control in zones ; it is kept at 1500–1700° F. and is supplied with a slightly reducing atmosphere.   The atmosphere for the pickling muffle is produced by burning a hydrocarbon gas with chlorine gas and air.   For example, one part of methane burned with two parts of chlorine and five parts of air produces a mixture of four parts of hydrogen chloride, one part of carbon dioxide and four parts of nitrogen.   This mixture is diluted and cooled to the pickling temperature of about 1350° F. by an addition of an equal amount of dehydrated flue gas produced by burning natural gas and air. The dry atmosphere for pickling thus consists of about 20% of HCl gas, 10% of CO_2 and the remainder nitrogen.   The vaporised chlorides formed in the furnace, together with unreacted gases, are withdrawn from the muffle through two hot exhaust wash legs just inside the charging end of the furnace.   A layer of non-volatile nickel and chromium chlorides forms on the inside of the alloy steel muffle and protects the metal from further attack.   The whole pickling line is run on a constant tonnage basis ; thus 0·025-in. strip is run twice as fast as 0·050-in. material.   The pickling time varies from 10 sec. for light gauges to 1 min. for heavy gauge strip.   Micrographs at high magnifications of acid-pickled and gas-pickled steel surfaces are reproduced for comparison.   The former surface is usually jagged and crystalline and looks as though whole grains of metal had been removed from the surface ; the gas-pickled surface can best be described as sub-crystalline etched and it presents a much greater gripping area per unit of surface for any subsequent coating.

COATING OF METALS

(Continued from pp. 83 A–86 A)

Protective Coatings for Metals.   H. G. Pyke.   (Australian Institute of Metals : The Australasian Engineer, 1944, vol. 44, Mar., pp. 33–35,

57–75). The various means of preventing the corrosion of metals by protective coatings are considered on the basis of atomic structure. Protective coatings are dealt with under the following headings : Assisted self-protection ; alloying for protection ; metallic coatings ; cladding ; hot-dipping ; cementation ; metal spraying ; simple replacement ; electro-deposition ; inorganic coatings ; and organic coatings. A bibliography is appended.

Inspection Tests for the Adhesion of Electroplated Coatings with Particular Reference to the B.N.F. Adhesion Test. A. W. Hothersall and C. J. Lead-beater. (Journal of the Electrodepositors' Technical Society, 1944, vol. 19, pp. 49–62). The difficulty of standardising the usual methods for the inspection of electroplated protective coatings is pointed out. An adhesion test for non-adherent or very slightly adherent coatings of up to 0·002 in. in thickness, developed by the British Non-Ferrous Metals Research Association, is described. The apparatus consists essentially of a ball-ended hammer, fixed to a flexible shaft mounted on a steel reed which is vibrated by means of a fluctuating magnetic field. The usual action of the hammer is to cause a non-adherent deposit to expand locally, producing a blister. Blistering or flaking occurs after 10 sec. The deposit is con-sidered to have passed the test if no blistering or flaking is produced within 1 min. Results of application of the test to fifty-two commercially-plated articles are reported.

New Nickel-Iron Alloy for Electroplating. A. H. Du Rose and P. R. Pine. (Steel, 1944, vol. 114, June 12, p. 124). A method for the simul-taneous electrolytic deposition of nickel and iron on steel has been developed. Few details are given but it is said to be possible to deposit coatings within the range of iron 5% and nickel 95% to iron 45% and nickel 55%.

Zinc Plating of Large Aircraft Structures. M. Sanz. (American Electro-platers' Society : Iron Age, 1944, vol. 153, June 15, pp. 64–70). The equipment and technique employed in the zinc plating of large and complex aircraft structures are described. The cleaning and passivating practices are discussed and data on changing the tanks from cadmium- to zinc-plating practice are presented.

The Effect of the Carbon Content of Steel Sheets on Their Galvanising Properties. W. Püngel. (Stahl und Eisen, 1944, vol. 64, Feb. 17, pp. 101–105). Tests are reported in which the effect of carbon in the 0·06–0·78% range in steel sheets on the structure, uniformity and adhesion of zinc coatings was studied. When the sheets were sand-blasted before galvanising the carbon content had no effect on the properties of the coating. The zinc coating on steel prepared by pickling only was not uniform and had black markings which were more numerous with increasing carbon content. In general it can be said that increasing the carbon content of the steel has no detrimental effect on hot-dip zinc coats on steel, but it is essential to coat on to a very clean surface.

Repairing Damaged Areas in Galvanized Coatings. F. D. McBride. (Steel, 1944, vol. 114, June 12, pp. 106–109, 152–154). The development of a tin-zinc-lead alloy with a suitable flux for the repair of damaged zinc coatings on steel and the method of applying it are described. The composition of the alloy is not stated but it contains more than 8% of zinc.

Rustproofing Process for Tinplate Food Can Packs. (Tin Research Institute : Sheet Metal Industries, 1944, vol. 19, June, pp. 1005–1006). A chemical filming treatment for rust-proofing tinplate has recently been devised by the Tin Research Institute. Details of the process are not given, but its practical advantages are : (1) It admits of rapid treatment with existing plant at negligible cost ; (2) treated tinplate is protected against corrosion by the atmosphere, by condensation, or by cooling and washing waters ; (3) the treatment prevents internal staining of the can when used

for meat, soup and many vegetable and fish packs ; (4) the protective oxide film is so thin that the eye cannot detect it ; (5) the process can be applied to tinplate sheets, to body blanks and can ends, or to finished cans ; and (6) the treatment simultaneously degreases and films the tinplate surface.

Tinning Cast Iron. R. A. Cresswell. (Foundry Trade Journal, 1944, vol. 73, June 15, pp. 129–130). As a result of considerable research at the Tin Research Institute a method has been developed by which a wide range of cast irons can be successfully hot-tinned. Details cannot be divulged without the sanction of the Ministry of Supply. A test for determining the adhesion of a white-metal lining to a cast-iron bearing is described.

Black Oxide Finish for Stainless Steel. I. C. Clingan. (Steel, 1944, vol. 114, May 22, pp. 80–81). A process of imparting a black oxide finish to stainless steel which improves its resistance to attack by hot nitric and hydrochloric acids is described. After cleaning, the parts are immersed in a solution of dichromates, preferably sodium dichromate, at a temperature above 615° F.

Procedures for Testing Metallizing Bond. H. Ingham and K. Wilson. (Welding Journal, 1944, vol. 23, May, pp. 411–415). In an effort to standardise testing methods for the adherence strength of sprayed metals, two testing procedures are described. One is a test for shear strength and the other for tensile strength, both of which affect the bond strength. The theory of the structure of the bond between the metal surface and the sprayed coat is briefly reviewed and the effect of internal stresses in the sprayed metal is considered.

Protective Painting of Iron and Steel (Other than in Buildings). (British Standards Institution, War Emergency British Standard 1160 : 1944).

Antifouling Paints. G. H. Young, G. W. Seagren, W. K. Schneider and J. C. Zehner. (Industrial and Engineering Chemistry, 1944, vol. 36, Apr., pp. 341–344). Quantitative measurement of the comparative rates at which painted steel panels (scratched along the diagonals on both front and back faces) corrode when immersed in sea-water shows that the intensity of the attack appears to vary directly with the concentration of copper pigment in the antifouling coat. It is shown that such attack may be eliminated by means of intermediate barrier coats.

PROPERTIES AND TESTS

Hairline Cracks in Steel. D. Cathcart. (Metal Treatment, 1944, vol. 11, Summer Issue, pp. 112–116, 111). The causes of hairline cracks in steel are reviewed and the methods of detection, the effects of hydrogen, steel composition, cooling stresses and of the steelmaking process on their formation are discussed.

The Non-Destructive Testing of Metallic Components. B. Chalmers. (Physical Society : Metal Treatment, 1944, vol. 114, Summer Issue, pp. 117–124). A general survey is given of the methods in use for the non-destructive testing of metals, together with the application of these methods in measuring dimensions, detecting flaws, estimating physical properties and examining surfaces.

Fluorescence as an Aid to Inspection. J. Brennan. (Metallurgia, 1944, vol. 30, June, pp. 70–72). The properties of fluorescent materials which are of importance in their application for inspection purposes are briefly described. Two methods of applying these materials for the

detection of cracks, flaws, porosity and surface imperfections are discussed ; one was designed for the laboratory and the other for production use.

Magnetic Particle Inspection. C. E. Betz. (American Society for Metals : Canadian Metals and Metallurgical Industries, 1944, vol. 7, May, pp. 30–34, 44–45). The principles of operation of the Magnaflux method of inspection are briefly described with notes on the merits and limitations of a number of different techniques.

Sheet Fractures Detected with Supersonics. (Iron Age, 1944, vol. 153, June 8, pp. 60–61). German supersonic equipment which enables inter-crystalline fractures parallel to the surface of steel sheet to be detected by non-destructive means has been developed. The new method is described from information taken from a number of German sources. References are included.

Relationship of Brinell Hardness and Yield Stress in Certain Cast Steels. T. W. Ruffle. (Institute of British Foundrymen : Foundry Trade Journal, 1944, vol. 73, June 20, pp. 227–231). A method is described and results are given for the use of the Brinell hardness test as a check on the yield stress of 100-lb. steel castings. The following points were investigated in detail : (1) The Brinell hardness and ultimate stress of separately cast test-pieces ; (2) the yield ratio of the test-pieces ; (3) the hardness and yield stress of the test-pieces ; and (4) the agreement in hardness between test-pieces and castings.

The Magnetisation of Polycrystalline Iron and Iron-Silicon Alloys. G. C. Richer. (Iron and Steel Institute, 1944, this Journal, Section I). During the immediate pre-war decade substantial advances were made in the domain theory of ferromagnetism, but investigational work on carefully prepared and highly purified single-crystal specimens often revealed a disappointing lack of accord between theory and observation. In view of the importance of the subject in its relation to improvements in the ferro-magnetic performance of the polycrystalline electrical sheet steels which constitute the essential constructional foundation of electrical generators, motors and transformers, a new survey has been made of the competency of the domain theory to account for the observed characteristics of such material. The general conclusion arrived at is that the basic theory, in a very simple form, can provide reliable guidance for industrial effort, but that certain as yet unexplained but inherently significant disharmonies between theory and observation are common to laboratory single crystals and to commercial polycrystalline aggregates. The survey has also yielded a new method of analysis of the technical magnetisation curve, which may be of general utility in assessing variations in the distribution of lattice orientation in ferromagnetic specimens.

Multi-Specimen Testing Equipment for Long-Time Creep Tests. A. Thum and K. Richard. (Archiv für das Eisenhüttenwesen, 1943, vol. 17, July–Aug., pp. 29–33). The design of two vertical electric furnaces with special holding and testing mechanism for the creep-testing of up to 400 specimens simultaneously is described in detail. The temperature of the furnaces is continuously recorded and automatically controlled. The specimens are arranged vertically in strings of four or eight according to their length and the stress is applied by tightening, at fixed time intervals, spring-loaded nuts on extension rods which project above the top plate of the furnace. The specimens are removed from time to time and the increase in length in the cold state with no load is measured.

High-Temperature Alloys for Dynamic Loading. C. T. Evans, jun. (Iron Age, 1944, vol. 153, June 1, pp. 38–41). Factors to be considered in the selection of alloys for use in new war weapons such as the jet-propelled aeroplane are briefly analysed. Methods of graphically presenting the results of tensile and creep tests at increasing temperatures and their

application in the selection of alloys for high-temperature service are explained.

Thermal Expansion of High-Silicon Cast Iron. P. Hidnert and G. Dickson. (Journal of Research of the National Bureau of Standards, 1944, vol. 32, Apr., pp. 145–149). An investigation of the thermal expansion of two 14%-silicon cast irons containing 0.05% and 3.0% respectively of molybdenum at temperatures between $20°$ and $700°$ C. is described. The difference between the coefficients of expansion of the two irons was slight. For temperatures between $20°$ and $300°$ C. the coefficients of expansion were slightly higher than that of electrolytic iron; at above $300°$ C. they were appreciably higher. There was no indication of growth similar to that of ordinary cast iron when the high-silicon iron was heated to $700°$ C.

16 : 2—The Forgotten Stainless Steel. M. E. Tatman. (Iron Age, 1944, vol. 153, May 11, pp. 70–71, 160). The use of 16/2 chromium-nickel steel is gaining favour in the United States for seaplane construction. Data on the mechanical properties and microstructure of this steel after various heat treatments are presented and discussed.

Improved 12 per Cent Chromium Steel Containing Molybdenum. (Metals and Alloys, 1943, vol. 18, July, pp. 55–62). A report on the effect of additions of molybdenum and silicon to 12%-chromium steel is presented. Room-temperature tests on bars containing 0.5%, 1.0%, 1.5% and 2.0% of molybdenum revealed that the steel with 1% of molybdenum had the best tensile properties. The molybdenum-treated steels had no tendency to temper brittleness. The effect of increasing the silicon from 0.34% to 1.10% in the 1%-molybdenum 12%-chromium steel was also studied. The 1.10%-silicon steel hardened less in air and had surprisingly low impact values in relation to its other properties after tempering. In the annealed condition there was little difference between the two steels. The increase in silicon had no detrimental effect on the strength properties of the steel in short-time tests at $1000–1300°$ F.

The Properties of Thorium-Bearing Heat-Treatable Steels. H. Cornelius. (Archiv für das Eisenhüttenwesen, 1943, vol. 17, July–Aug., pp. 23–27). An investigation of the effect of additions of thorium to three low-alloy steels (alloyed with vanadium, chromium and molybdenum, respectively) and one plain carbon steel, all containing about 0.3% of carbon and about 1.8% of manganese, is described. The effect of adding up to 1.4% of thorium to heat-treatable steels is governed primarily by the formation of the exceedingly stable carbide ThC_2, which is practically insoluble in solid iron at temperatures up to $1340°$ C. In spite of this, the hardening temperature range is only extended a little. The effect of the insolubility of thorium carbide in solid iron is that the steel loses its heat-treatability entirely if the thorium content amounts to about ten times the carbon content and is sufficient to convert all the carbon into thorium carbide. The presence of large amounts of thorium carbide in heat-treated steel reduces its toughness. The scaling-resistance of the steels at $650°$ and $800°$ C. was not improved by the addition of thorium. If the thorium addition exceeds a few tenths of 1% the effect is likely to be detrimental.

Steel Reclassification. A. L. Hartley. (Steel, 1944, vol. 114, June 26, pp. 86–87, 136). The author states that classification of steels will be one of the necessary factors in reducing production costs in the post-war period. A brief outline is given of a general procedure for the establishment of a programme for standardising the classification of steels.

METALLOGRAPHY AND CONSTITUTION

A Five-Year Plan for an Australian Metallurgical Institute. R. S. Russell. (Australian Institute of Metals : Australasian Engineer, 1944, vol. 44, May 8, pp. 26–31). The author explains why the five branches of the Australian Institute of Metals should become legally incorporated and set up a Federal Council. He suggests that the institute should adopt a policy involving : (1) A radical change in the broad general objects for which research hitherto has usually been conducted ; (2) setting up a new public body for carrying out research ; (3) improved facilities for the co-ordination and application of existing knowledge ; and (4) increased co-operation with other branches of science and art, with the object of developing an increased understanding of the art of living.

Metallography in Color. R. P. Loveland. (A.S.T.M. Bulletin, 1944, May, pp. 19–29). The principles of colour photography are explained and its application to metallography with special reference to the use of the Kodachrome film is described.

An Inexpensive Photometer for Metallographers. P. A. Haythorne and R. W. Powell. (Iron Age, 1944, vol. 153, May 11, pp. 66–69). A description is given of a photometer and its application in the photomicrography of metallographic specimens.

A Rapid Electrolytic Process for the Etch-Polishing of Metal Sections. A. L. De Sy and H. Haemers. (Iron and Steel Institute, 1944, Translation Series, No. 186). An English translation is presented of a paper which appeared in Stahl und Eisen, 1941, vol. 61, Feb. 20, pp. 185–187 (see Journ. I. and S.I., 1941, No. II, p. 29 A).

The Structure of Metals and Alloys. J. McAfee. (Australian Institute of Metals : The Australasian Engineer, 1944, vol. 44, Mar., pp. 23–29). The crystal structure of metals and a number of well-known alloy systems are considered from the point of view of inter-atomic binding forces. Evans' classification of alloy systems on the basis of the periodic table is used to indicate how a systematic approach to the whole subject can be made.

The Carbides in the Iron-Manganese-Carbon System. E. Öhman. (Iron and Steel Institute, 1944, Translation Series, No. 191). An English translation is presented of a paper which appeared in Jernkontorets Annaler, 1944, vol. 128, No. 1, pp. 13–16 (see p. 60 A).

CORROSION OF IRON AND STEEL

The Salt Spray Test. V. M. Darsey. (A.S.T.M. Bulletin, 1944, May, pp. 31–34). Attempts have been made in the United States to establish a standard salt-spray test. One difficulty is that of measuring and maintaining a uniform fog of salt solution inside the test cabinet. A quantitative method of calibrating a fog formed by atomising a 20% sodium-chloride solution with air at 10 lb. per sq. in. in a cabinet 7 ft. 3 in. × 7 ft. 2 in. × 8 ft. 4 in. high is described.

Surface Protection of Aircraft Parts. V. S. Sorenson and S. G. Andrews. (Iron Age, 1944, vol. 153, May 18, pp. 74–77). A research programme carried out by the Lockheed Aircraft Corporation in an effort to solve

finishing problems arising from the increased use of low-carbon steels in place of nickel-bearing stainless steels is described. The problem of galvanic corrosion in aircraft construction is discussed. The results of investigations on comparative protection afforded by various combinations of phosphate treatments and additional coatings are given, and finishes now in use on various steel parts are also listed.

Accelerated Corrosion of Tin Cans in Various Types of Solid Fibre Containers. C. E. Libby, F. W. O'Neil and A. W. Nickerson. (Canning Trade : Sheet Metal Industries, 1944, vol. 20, July, pp. 1189–1190). A brief report is given of the results of an investigation of the conditions causing corrosion to the outside of tin cans packed in various types of fibreboard boxes. Batches of cans in containers were put in a kiln and held for 24 hr. at 140° F. in a controlled humid atmosphere and were then cooled to 60° F. in a further 24 hr. in the kiln. The corrosion appeared to be due to the chemical action of the material binding the fibre of the container.

Some Notes on Benzol Plant Corrosion. J. M. Todd. (Yearbook of the Coke Oven Managers' Association, 1944, pp. 85–91). Corrosion which takes place in the refining-plant condensers of a benzole plant is discussed. Assuming that corrosion is caused by sulphur dioxide produced by the breakdown of cyclopentadiene and dicyclopentadiene during acid treatment, the author considers the following methods of dealing with the trouble : (a) Modification of the refining process to give minimum production of sulphur dioxide in the refining still ; (b) neutralisation of corrosive vapours ; (c) use of corrosion-resisting materials ; (d) design of a condenser such as will admit of rapid cleaning and/or replacement of corroded parts ; (e) use of some readily-corrodible material in the vapour stream immediately before the condenser ; and (f) use of vacuum distillation.

A Suggested Standard Method for the Examination of Anti-Corrosive Primers. P. M. Fisk. (Sheet Metal Industries, 1944, vol. 20, July, pp. 1217–1220). A method of testing corrosion-resisting priming paints is described. Test panels 9 × 4 in. were mechanically cleaned and five rectangles each 2¼ × 1 in. were sprayed on each panel with a primer-filler paint having practically no resistance to weathering. This coating was stoved, cooled and rusted in a " weatherometer " so that the whole panel was coated with rust and partially weathered paint. This panel was cleaned with wire-wool and immediately coated with the primer to be tested. Two of the rectangles were deeply scratched and the panels were exposed to the continuous action of salt spray. In this way a good imitation of the actual conditions of painting gutters, metal window frames, &c., was obtained. This priming paint was then covered with a low-grade white paint of high moisture permeability which was to act as a detector coat for the effects of corrosion. The resistance of the primer to corrosion depends on its permeability to moisture ; thus, those based on phenol-formaldehyde, wood oil or chlorinated rubber are, generally speaking, the best. On the whole, paints containing metallic pigments such as atomised lead or zinc give better results than paints based on chromates, red lead, or red oxide.

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MINERAL RESOURCES

Large-Scale Superficial Structures in the Northampton Ironstone Field. S. E. Hollingworth, J. H. Taylor and G. A. Kellaway. (Quarterly Journal of the Geological Society of London, 1944, vol. 100, pp. 1–35). A detailed description of superficial structures in the Northamptonshire ironstone field is given. The economic significance of the structures in the exploitation of ironstone and in water supply are briefly considered and reference is made to analogous structures in other areas.

British Iron and Steel. (Metallurgia, 1944, vol. 30, July, pp. 135–138, 164). The history of the development of iron and steel making is reviewed. A table of the actual and potential reserves of iron ore in different countries is presented and their significance for Great Britain and the United States discussed. England has large reserves, but the grade is low and requirements are high, necessitating considerable importation of better-grade ore. This fact, and the knowledge that fuel costs will be high, will necessitate very careful organisation and the best use of available plant so as to achieve economy in production. Plant will have to be modernised and arrears of repairs and maintenance made up as quickly as possible in the post-war period.

Iron Ores of the Pacific Northwest. C. Zapffe. (Steel, 1944, vol. 114, Apr. 10, pp. 116–118, 136–141). Mineralogical and chemical analyses of the iron ores of Okanogan County, Kittitas County and Skagit County, Washington, are presented and the possibilities of exploiting them are discussed.

Wartime Necessity Has Spurred Development of Brazil's Resources. (Machinist, 1944, vol. 88, July 29, pp. 102–104). A brief account is given of the industrial expansion of Brazil from 1918 until the present day. A list of the chief mineral resources of Brazil is given.

ORES—MINING AND TREATMENT

(Continued from pp. 32 A–33 A)

Iron Ore Mining and Processing in New York. (Engineer, 1944, vol. 178, Aug. 18, pp. 122–123; Aug. 25, pp. 151–152). There has been a revival, on a large scale, of the mining and processing of the extensive deposits of iron ore in the Adirondack region in the north-east of New York State. Methods of mining and concentrating the ore on the Mineville and Port Henry property are described.

Nodulizing Iron Ore. G. E. Seil. (Iron Age, 1944, vol. 153, Apr. 27, pp. 40–46). The preparation of ores by nodulising in rotary kilns is compared with sintering. The design of kilns with particular reference to the oil-burners and air supply is described and illustrated and recommendations for operating rotary kilns are made.

Fine-Screening Investigations. Part I. S. Mörtsell and P. V. Villner. (Iron and Steel Institute, 1944, Translation Series, No. 175). An English translation is presented of a paper which appeared in Jernkontorets Annaler, 1943, vol. 127, No. 4, pp. 98–128 (*see* Journ. I. and S.I., 1943, No. II., p. 179 A).

FUEL

The Combustion of Coal of High Ash and Moisture Content in the Firing of Boilers. H. Lent. (Zeitschrift des Vereines Deutscher Ingenieure, 1943, vol. 87, May 1, pp. 241–250). Suitable designs of grates and boilers for firing inferior coal high in ash and moisture are described and illustrated.

Saving Fuel by the Utilisation of Waste Heat behind Gas Engines for Blowers. G. Prieur. (Stahl und Eisen, 1944, vol. 64, Jan. 27, pp. 62–64). An example is given of the calculations necessary for determining the amount of heat available in a modern waste-heat boiler plant utilising the exhaust gas from either one large and three small gas-engines driving blast-furnace blowers, or from five small gas-engines. The amount of coal which would be required in an old fire-tube boiler to produce an equivalent amount of energy in the form of steam is also calculated. The data apply to a blast-furnace plant consuming 40,000 tons of coke per month and producing 3900 cu. m. of blast-furnace gas at N.T.P. per ton of coke. The saving in coal consumption with the waste-heat boiler plant amounted to 400–420 tons per month.

Heat Transfer—Conduction, Radiation and Convection. H. J. Stoever. (Chemical and Metallurgical Engineering, 1944, vol. 51, May, pp. 98–101, 106, 107). Satisfactory solutions to some heat-transfer problems can be obtained by fairly simple equations. The derivation and use of the more important of these equations are briefly explained. Tables and nomographs for the rapid determination of convection coefficients for a number of fluids under various conditions are presented.

Heat and Cold Production and Application for Processes. W. J. Shore. (Chemical and Metallurgical Engineering, 1944, vol. 51, May, pp. 109–117). The fundamentals of heat production, cooling processes and heat transfer are discussed with notes on how these affect furnace design.

Special Media for the Transfer of Heat. (Chemical and Metallurgical Engineering, 1944, vol. 51, May, pp. 118–119). The heating and cooling of process materials are often dealt with more effectively by a heat-transfer medium. The properties of a number of gaseous, liquid and solid heat transfer media are discussed.

Equipment for Heat Transfer and Heat Application. M. W. Schwarz. (Chemical and Metallurgical Engineering, 1944, vol. 51, May, pp. 120–128). Equipment for the following purposes is described and discussed : (1) Heating and cooling liquids, gases and solids ; (2) distillation of liquids ; (3) sublimation of solids ; (4) evaporation of liquids ; (5) drying solids plus liquids ; (6) condensation of vapours ; (7) fusion of solids ; and (8) freezing of liquids.

Necessity for Coal Cleaning. W. T. Brown. (Mining Congress Journal : Blast Furnace and Steel Plant, 1944, vol. 32, Apr., pp. 457–458, 482, 483 ; May, pp. 557–561). The increased use of mechanical appliances for loading coal in the United States has led to an increase in the ash content of at least 2% as well as to an increase in the sulphur, and many plants have installed new coal-cleaning plant or increased the capacity of their washeries in consequence. The reasons why coal low in ash and sulphur is required for coke-ovens and for steam-raising are given and the forms of sulphur occurring in coal are described.

Pulverized Coal Firing of Metallurgical Furnaces. L. S. Wilcoxson. (Iron and Steel Engineer, 1944, vol. 21, June, pp. 74–83). The importance of sulphur content, fusing temperature of the ash, ash content,

volatile matter and grindability of coal in relation to the use of pulverised coal fuel is discussed. A comparison is made of the costs of firing a billet-heating furnace with oil and with pulverised coal. Examples of metallurgical furnaces heated by three pulverised coal systems are described. These are : (a) Where the pulverising plant supplies a large storage bin from which the coal is fed by a pneumatic transport system to smaller individual bins adjacent to the burners ; (b) the direct-fired unit system in which the burner lines are taken directly from the pulveriser, so that the air used through the pulveriser to pick up the coal constitutes the primary air for combustion ; and (c) the direct-fired circulating system for several furnaces of small capacity in which the pipe carrying the pulverised coal and its primary air forms a continuous loop passing each furnace ; the pulverising machinery can be installed at any convenient position on the loop and may be a considerable distance from the furnaces.

Production and Use of Low-Temperature Char as a Substitute for Low-Volatile Coal in the Production of High-Temperature Coke. J. D. Price and G. V. Woody. (American Institute of Mining and Metallurgical Engineers, 1944, Technical Publication No. 1745). Many coke producers have studied the problem of finding a substitute for low-volatile coal for mixing with high-volatile coking coal for charging high-temperature coke-ovens. An account is given of the experimental work and the results obtained by the Colorado Fuel and Iron Corporation in producing and using low-temperature " char " for this purpose. Char is produced by the partial devolatilisation at a low temperature of high-volatile coal, and the blending of this char with the high-volatile coking coal has definitely improved the quality of the coke made from Colorado coal.

The Importance of the Dry-Cooling of Coke in Coke-Oven Practice. W. Scheer. (Stahl und Eisen, 1944, vol. 64, Jan. 27, pp. 53–62). The theory and practice of methods of utilising the heat given up when coke is cooled by dry methods are discussed. Descriptions are given of the Sulzer and Collin processes with actual cost and steam-production data for four plants. The following conclusions are arrived at : (1) The technical progress made in dry methods of cooling coke is such that the amount of steam produced is equivalent to about 2·7% of the calorific value of the coke. (2) The economy of the dry-cooling process depends to a large extent upon local conditions ; if these are favourable, steam can be produced at 1·25 RM. per metric ton. (3) In some respects dry-cooled coke has advantages over water-quenched coke and these must be taken into account when comparing costs. (4) In peace-time, when constructional material is available, more thought should be given to the dry-cooling of coke because the process is an important source of energy. (5) The best way to utilise the heat in coke discharged from ovens or retorts is for steam-raising ; the production of water-gas is out of the question.

The Permeability of Coke. W. Brewin and R. A. Mott. (Fuel in Science and Practice, 1944, vol. 23, July–Aug., pp. 90–99). A laboratory investigation of the permeability of coke is described. Coke is relatively impermeable to the passage of gas and the resistance is such that, during combustion with air at low pressure, only a negligible amount of air can penetrate through the porous structure of the coke. The resistance to the passage of gas is directly proportional to the length and inversely proportional to the area exposed. The resistance is approximately three times as high in a plane at right angles to the oven wall compared with that parallel to the oven wall. This difference indicates that, as the coke is forming, gas passes in a plane parallel to the oven wall, as a result of which the pores in coke are oriented in this plane. The permeability of coke does not appear to be an important factor in the combustion of coke, and there is no simple relationship between permeability and reactivity.

Mechanical Developments in Modern Metallurgical Gas Producers. F. Reddet. (Sheet Metal Industries, 1944, vol. 19, Mar., pp. 441–443; Apr., pp. 795–802; June, pp. 989–993; July, pp. 1163–1171; Aug., pp. 1352–1355). An English translation is presented of a paper which appeared in Revue de Métallurgie, Mémoires, 1942, vol. 39, May, pp. 129–140 (*see* Journ. I. and S.I., 1944, No. I., p. 185 A).

PRODUCTION OF IRON

Dehydration and Oxygen Enrichment of Blast-Furance Air. J. B. Fortune. (Metallurgia, 1944, vol. 30, July, pp. 152–158). The results obtained in America by dehydrating blast-furnace blast and on the Continent and in the U.S.S.R. by working with oxygen-enriched blast are reviewed. The benefits likely to be obtained by using dehydrated blast will be at a minimum at highly efficient plants where the burden is prepared by ore grading and beneficiation, by coke sizing, by crushing and screening the limestone and by controlling the blast volume and temperature. Where adverse conditions still obtain there is more to be gained by adopting these features than by drying the blast. The Air Blast Committee of the British Iron and Steel Federation reported in 1935 that it was doubtful whether the savings which would be effected by adopting in England the process of oxygen-enrichment tried by the Gutehoffnungshütte at Oberhausen would justify the capital outlay and operating costs.

Ironmaking at the Appleby-Frodingham Works of The United Steel Companies, Limited. G. D. Elliot and the Staffs of the Appleby-Frodingham Ironworks, Scunthorpe, and of the Central Research Department, Stocksbridge (The United Steel Companies, Ltd.). (The Iron and Steel Institute, 1944, Special Report No. 30). This report is divided into eleven Sections, dealing with all aspects of ironmaking at Appleby-Frodingham, from the mining of the iron ore to the production of pig iron.

SECTION I.—*Brief History of Ironmaking at Appleby-Frodingham.*— The history of the blast-furnaces at Appleby-Frodingham from 1866 to the present day is touched upon.

SECTION II.—*The Blast-Furnace Burden.*—Frodingham and Northampton ironstones are briefly described and typical analyses given. Crushing, screening and drying operations are described. The variability of the ores is shown to demand some means of blending, which is done in the Robins-Messiter bedding plant. Two types of sintering plant are described briefly and attention is drawn to various operating problems. Free lime in the ores leads to a weak sinter. The effects of bed porosity and the importance of air supply are considered. The use of sinter in the furnace burden, with particular reference to the optimum amount, is discussed. The Section includes results of laboratory tests on ores and sinters, especially with regard to reducibility. Experimental sinters have been investigated.

SECTION III.—*Furnace Plant Design and Layout.*—The difficulties of furnace design are discussed and certain principles are laid down for Appleby-Frodingham furnaces. The importance of the stack section and of stack batter is dealt with. A shortening of the bosh may be more effective than a steepening of the bosh angle. Five campaigns of No. 4 furnace are compared to illustrate the problem of design. The use of

bosh tuyeres and their elimination are mentioned.   Cast-house layout and points of more mechanical detail are dealt with.

SECTION IV.—*Blast-Furnace Coke.*—The chief aspects of coke-oven operation are described and statistical methods are used to correlate them with the behaviour of blast-furnaces using the coke produced.   Attention is drawn to the need for consistency in all operating factors, and examples are given to show that there are greater variations in raw material than in operating procedure.   The difficulty of finding an index of coke quality is described and the limitations of existing methods are indicated.   Further research is asked for into those properties of coke which may influence its behaviour in the blast-furnace.   Notes on volatile matter in coke are appended.

SECTION V.—*Blast-Furnace Refractories.*—The properties of several brands of bricks are listed.   Results of a twenty-months' weathering test show that loss of strength due to storing bricks in the open is negligible compared with variations observed in a new consignment.   The action of ferrous chloride on firebricks has been examined.   Under the test conditions, deposition of ferrous chloride did not lead to disintegration of the bricks.   The attack on firebrick by blast-furnace slag has been studied. Work in connection with tap-hole clays leads to the conclusion that the bloating of a suitable clay at about $1100°$ C. may be a factor in the successful use of that clay.   Notes on the care and maintenance of tap-holes are given.   The development of carbon brick refractories is discussed, together with notes on tests conducted in furnace runners and while repairing breakouts.

SECTION VI.—*Hot-Blast Stove Refractories.*—Research on stove refractories is described.   The effects of the rigidity of the brick are discussed, especially in connection with alkali attack.   Notes on stove design and the results of an efficiency test are included.

SECTION VII.—*Furnace Operation and Operating Problems.*—Furnace managers are handicapped by the lack of fundamental knowledge of the process.   Notes on blast, burden and slag control are given.   The influence of the size of furnace on slag basicity is stressed.   Mention is made of cast-house routine.   The problems associated with iron quality, slag volume, &c., are mentioned and the problem of hanging is dealt with in some detail.   The need for more publications of a practical nature is emphasised.   Stock distribution is dealt with at some length.   The influence of the angle of repose, and the bulk-densities of the ore and the coke are discussed.   Attention is drawn to the effects of the throat diameter and to vertical segregation at the stockline.   The use of sodium carbonate as a slug or cleaner is described.   The problem of shoddy (an iron-slag mixture which refuses to separate at the skimmer during casting) is mentioned.

SECTION VIII.—*Scaffolds.*—The removal of a stack scaffold by means of auxiliary tuyeres inserted through the stack-cooler openings is described. A theory of scaffold formation is put forward which shows that alkali cyanides may act as binders.   Scaffolds can be prevented if smooth stock descent is achieved.

SECTION IX.—*The Utilisation of Fuel in the Blast-Furnace.*—The views of various authors on the relative merits of " direct " and " indirect " reduction are discussed, and the question is raised as to which of the two reaction methods is the more economical in Appleby-Frodingham practice. The percentage of carbon burnt at the tuyeres has been calculated and graphed against the coke consumption, without direct evidence being found that this percentage affects the coke consumption.   It is shown that ore reducibility and coke reactivity are the principal factors controlling the respective amounts of direct and indirect reduction, and that

carbon is lost to the furnace by the action of an excessive amount of moisture in the ore.

Section X.—*Hearth Breakouts.*—Actual breakouts and repairs are described in detail. A detailed investigation into the causes of breakouts is described, and a theory of breakouts is developed.

Section XI.—*Lifting of the Blast-Furnace Superstructure.*—Detailed examination of refractory bricks from a furnace which had burst its casing owing to upward movement showed carbon deposition to be the cause. Measurement of normal upward expansion is described.

Considerations on Blast-Furnace Practice.—T. P. Colclough. (Iron and Steel Institute, 1944, this Journal, Section I). Theoretical considerations and practical experience indicate that considerable economies in coke consumption may be effected in many blast-furnaces. To secure these economies it is necessary to attain a higher efficiency in the combustion of the carbon used within the furnace and to reduce as far as possible the weight of the slag-forming oxides charged in the burden. It is highly desirable that a survey shall be made of British ores to determine the maximum size to be charged into the furnace on the basis of their thermal conductivities and permeabilities to gas penetration. The ores of high lime or silica content should be examined to determine their response to roasting and magnetic separation. All British ores should be mixed, crushed and graded before being charged into the furnace, and all charging should be based on ore size and not quality of ore. All fines should be removed from the mixture and sintered before use in the furnace. It is to be anticipated that with the correct preparation of the British ores, the reduction in coke consumption to be effected will be of the order of at least 20% as compared with common practice.

Nitriding Ferroalloys. R. H. Steinberg and D. Steinberg. (Metals and Alloys, 1944, vol. 19, Apr., p. 859). It is possible to produce nitrogen-bearing ferro-chromium, the nitrogen assisting in refining the grain when making stainless steel. As the addition of nitrogen to other ferro-alloys might also be useful, tests were made to establish how much nitrogen was taken up in 1 hr. when samples were nitrided with ammonia gas at different temperatures. 16% ferro-silicon absorbed 9·3% of nitrogen at 1110° F., but 78% ferro-silicon would not absorb any nitrogen at all. The optimum temperature for 80% ferro-manganese was 1290° F., at which it took up 10–11% of nitrogen.

Explosibility of Metal Powders. I. Hartmann, J. Nagy and H. R. Brown. (United States Bureau of Mines: Metal Progress, 1944, vol. 45, May, pp. 886–887, 930–932; Metal Industry, 1944, vol. 65, Aug. 18, pp. 103–104). The factors affecting the relative inflammability of metal powders are discussed and tables are presented showing the relative inflammability, ignition temperature of dust cloud, maximum pressure and maximum rate of pressure rise for milled iron, reduced iron, carbonyl iron and a number of non-ferrous metal powders.

Presses and Processes for Metal Powder Products. E. V. Crane and A. G. Bureau. (Electrochemical Society: Iron Age, 1944, vol. 153, June 29, pp. 36–41; vol. 154, July 6, pp. 62–67). *See* p. 72 A.

FOUNDRY PRACTICE

The Ironfounding Industry and Co-operative Research. H. Hartley. (Metallurgia, 1944, vol. 30, July, pp. 149–151). The need for extensive

co-operative research in the ironfounding industry of Great Britain is emphasised. A progressive industry should be prepared to spend 1% of its turnover on research and development and, of this, one-fifth could with advantage be employed for work done on a co-operative basis. The Council of the British Cast Iron Research Association envisages further expansion of activity after the war, based on an income of £60,000 per annum.

The Making of High-Duty Iron Castings to Specification. E. Hunter. (Engineering Inspection, 1944, vol. 9, Summer Issue, pp. 23–30). A description is given of the method of control employed at an iron foundry handling approximately 1000 patterns per week and where it is necessary to use from ten to twelve processes daily for melting. Rigid technical control is exercised and is sub-divided into five sections, viz. : Laboratory, metallurgical processes, pattern and equipment inspection, quality control and final inspection. These sections are co-ordinated by a statistical control system.

Factors in the Production of Quality Castings. W. G. Reichert. (Institute of British Foundrymen : Foundry, 1944, vol. 72, Feb., pp. 115, 199–202 ; Mar., pp. 114–115, 190–195 ; Apr., pp. 130, 218–228). The factors affecting the production of castings of high quality which are discussed include : Pattern design, control of moulding sand, maintenance of air pressure for moulding machines and directional solidification. The positioning of gates and risers to prevent internal shrinkage in castings of different design is explained and in conclusion the control of melting and pouring practice is described.

Structure Control of Gray Cast Iron. R. G. McElwee and T. E. Barlow. (Foundry, 1944, vol. 72, Feb., pp. 112–114, 177, 178 ; Mar., pp. 104–105, 163, 164 ; Apr., pp. 133, 256–259). Distinction is made between additions of alloying elements and of inoculants to grey cast iron. The technique for adding inoculants is described and the benefits which can be obtained by it are discussed.

" Monometer " Tilting and Rotary Metal-Melting Furnaces. (Engineering, 1944, vol. 158, Aug. 25, p. 146). Illustrated descriptions are given of new small tilting and rocking furnaces. One is a 3-ton open-hearth type and is used for storing molten iron from cupolas. The furnace may be gas- or oil-fired, and preheated air is employed.

Steel Mixes and Inoculants in Grey Cast Iron. W. Barnes and C. W. Hicks. (Institute of British Foundrymen : Foundry Trade Journal, 1944, vol. 73, Aug. 10, pp. 287–292 ; Aug. 17, pp. 313–319 ; Aug. 24, pp. 337–341). An investigation is described the chief purpose of which was to measure the effect on physical properties of increasing percentages of steel in the cupola charge with and without a measured amount of various inoculants. The second purpose was to measure the effect of increasing percentages of steel and varying amounts of inoculants, and the third purpose was to ascertain the effect of increasing percentages of steel on the reaction of the iron produced to low-temperature treatment and to oil-quenching. The inoculants used were calcium silicide, ferro-silicon, aluminium, ferro-silicon and aluminium mixed, and nickel shot. The conclusions reached are : (1) Increasing the proportion of steel in the charge has the following effects : (a) It raises the tensile and transverse strengths ; (b) it gives greater stability to the iron-silicon carbides in grey iron so that its physical properties can be improved by oil-quenching and tempering ; and (c) it improves the internal soundness of heavy sections of castings, thus improving the machined finish. (2) The melting of steel scrap in the cupola is not a difficult practice and the cost is considerably less than when refined irons are used. (3) Although the addition of 1% of nickel appears to refine the graphite in iron made with a small

percentage of steel, its effect on the graphite in the higher steel mixtures is negligible; the increase in tensile strength does not justify the sharp increase in cost. (4) With grey iron at the spout, the normal silicon-base inoculants appear to act as deoxidising agents and the metal is improved by a small addition; adding aluminium alone has a greater scavenging action than a silicon addition. (5) Correct melting practice makes the melting of steel mixtures simple and straightforward and special cupolas are no more essential than they are for ordinary iron mixtures.

Pours Finned Cylinders of Alloy Cast Iron. E. Bremer. (Foundry, 1944, vol. 72, June, pp. 116–119, 260). A description is given of the technique employed at the foundry of the Motor Castings Company, Milwaukee, where finned cylinders for compressors, automobiles and aero-engines are made of low-alloy cast iron.

The Coreless Induction Furnace in the Steel Foundry. F. Harms. (Stahl und Eisen, 1944, vol. 64, Mar. 16, pp. 175–178). A description is given of the electric furnace plant at a steel foundry; this consists of two $2\frac{1}{2}$-ton and one $\frac{1}{2}$-ton coreless induction furnaces. Data on the current consumption, production and properties of the steel are presented. The advantages include the ease of temperature regulation, the rapid melting and the low loss of alloying elements. The disadvantages include the high capital cost. Where small quantities of very hot steel are wanted at frequent intervals, the coreless induction furnace is an ideal production unit.

Sandslinger Moulding Practice. W. Y. Buchanan. (Institute of British Foundrymen: Foundry Trade Journal, 1944, vol. 73, July 27, pp. 249–253; Aug. 3, pp. 275–278). The distribution of mould hardness which results from various methods of mould ramming is considered, special attention being paid to sandslingers. A special test to determine mould hardness in sandslinger practice is described.

Reclaiming Foundry Sand by the Wet Method. W. Rengering and W. Horth. (Iron Age, 1944, vol. 154, July 6, pp. 68–74). An account is given of preliminary investigations of methods of reclaiming used moulding and core sands at a large American foundry and of the equipment for the wet process which was selected as being the most economical.

Risering of Steel Castings—Graphite Rods in Blind Risers. J. W. Juppenlatz. (Metals and Alloys, 1944, vol. 19, Apr., pp. 874–879). The practice of " blind risering " has been explained by H. F. Taylor and E. A. Rominski and the use of graphite rods as vents in risers by F. J. Vosburgh and H. L. Larson (see Journ. I. and S.I., 1943, No. I., p. 77 A, and this Journal, p. 40 A). In the present paper some examples of this technique are described in which either graphite rods or oil-sand cores were built into the top of the riser to allow the pressure of the atmosphere to act on the surface of the metal. Recommendations on the position of the risers, their size and that of the gates are made.

Casting Steel Centrifugally. S. D. Moxley. (American Society of Mechanical Engineers: Steel, 1944, vol. 114, June 19, pp. 84–85, 148–154). The machinery and equipment for the centrifugal casting of tubes, bushes and flywheels in iron and steel are described.

Centrifugal Casting. J. E. Hurst. (Institute of British Foundrymen: Iron and Steel, 1944, vol. 17, July, pp. 533–536). Methods of calculating the rotational speed and the velocity of the metal during centrifugal casting are explained for the cases where the mould is spinning on a horizontal, inclined or vertical axis.

Centrifugal Castings. P. Blackwood and J. Perkins. (Canadian Metals and Metallurgical Industries, 1944, vol. 7, June, pp. 26–33). The technique for centrifugal casting developed by the Ford Motor Company of Canada, Ltd., is described. The articles cast by this method include

brake shoes, hand grenades, steel propellers, valves, aero-engine cylinder
barrels and milling cutters.

PRODUCTION OF STEEL

(Continued from p. 123 A)

Research and the Future of the British Iron and Steel Industry. D. A.
Oliver. (Metallurgia, 1944, vol. 30, July, pp. 139–142). A brief com-
parison is made between what has been achieved in the immediate past
by research in Great Britain and in other industrialised countries.
Still closer inter-company co-operation in the future provides one of the
most promising solutions to a large number of problems which confront
both individual organisations and different parts of the industry viewed
as separate units. In the past there has been a failure to undertake pilot-
plant development prior to running risks with the production organisa-
tions. There is a huge field of work to be undertaken which might be
broadly classed as an attempt to do what is being done now, but by
improved engineering or metallurgical technique, so that the overall cost
of the operations will be reduced.

**Some Aspects which Affect the Future of the British Iron and Steel
Industry.** J. Ross. (Metallurgia, 1944, vol. 30, July, pp. 143–144, 158).
During the war years all steel plants have been running at maximum
capacity with little time available for even ordinary maintenance ; existing
plants will therefore require a thorough examination with a view to
rehabilitation and modernisation. As the days of cheap fuel are gone,
continuous research in the design of furnaces of all types to reduce fuel
consumption and to secure a steady increase in the use of waste heat
for steam generation is required. The close co-operation of management
and labour is necessary to produce a flourishing iron and steel industry ;
some suggestions on how this can be achieved are made.

Labour and the Future of the Iron and Steel Industry. J. Brown.
(Metallurgia, 1944, vol. 30, July, pp. 145–148). With a view to avoiding
a repetition of the uncertainty and unemployment which occurred in the
iron and steel industry of Great Britain in the years following the war of
1914–18, a scheme for the participation of the State in the industry is
put forward and its advantages discussed.

Peru's New Iron and Steel Industry. (Iron and Coal Trades Review,
1944, vol. 149, July 28, p. 114). Particulars are given of plans for the
equipment of an iron and steel plant and of coal and ore mines in Peru.
Three areas are to be exploited, namely, Marcona, where iron-ore deposits
are to be mined ; the Santa and Chiquicara valleys, where coal is to be
mined ; and Chimbote, where the port is to be developed and made the
centre of a fully-integrated steel industry. The iron and steel plant will
include a coke-oven battery, a blast-furnace to produce 100 tons per day,
a duplex steel plant, rolling mills and a foundry.

**Construction of the Fontana Plant of the Kaiser Company, Inc., Iron
and Steel Division.** G. Havas. (Engineers' Society of Western Pennsyl-
vania : Blast Furnace and Steel Plant, 1944, vol. 32, May, pp. 551–556).
An account is given of some of the difficulties met with, and the means
by which they were overcome, in designing and constructing the iron,
steel and rolling-mill plant at Fontana, California.

The Manufacture and Properties of Killed Bessemer Steel. E. C.
Wright. (American Institute of Mining and Metallurgical Engineers,
Technical Publication No. 1692 : Metals Technology, 1944, vol. 11, June).

The method of making killed Bessemer steel developed by the National Tube Company, Pittsburgh, and the properties of this steel are described. After blowing, hot metal containing about 4% of carbon is added to the converter ; the steel is then poured into ladles to which ferro-silicon and aluminium are added to give final deoxidation. The yield strength and fatigue properties of the killed Bessemer steel at room and at sub-zero temperatures are superior to those of open-hearth steel of the same tensile strength. The ductility and toughness of the former steel both at room and at sub-zero temperatures are equal to those of the open-hearth steel of the same tensile strength, provided both steels are thoroughly killed with the same deoxidation practice. With steel of the same tensile strength the weldability of the killed Bessemer steel is superior to that of open-hearth steel. The creep strength of the fine-grained killed Bessemer steel is higher than that of fine-grained open-hearth steel finished with the same deoxidation practice.

The Effect of Melting Practice on the Properties of Steel. J. A. Preston. (Australian Institute of Metals : Australasian Engineer, 1944, vol. 44, June 7, pp. 31–35). After reviewing the acid and basic open-hearth and electric-furnace processes as practised in Australia, the author discusses those factors in the processes which govern the quality of the finished steel. The circulation of sufficient iron oxide is essential for the removal of the foreign bodies which cause low impact resistance and reduce the yield point. The presence of sufficient ferrous oxide dispersed throughout the bath and the carbon monoxide evolved by oxidation of the iron carbide tends to remove any hydrogen. Thus, the presence of sufficient ferrous oxide and a good " boil " are two important requirements in the first part of the steel-making process. The ferrous oxide, so useful in melting, must be removed in refining. If present in liquid steel in excess of 0·2%, it oxidises the manganese and silicon, causes loss of alloying elements and more inclusions. Silicon and manganese are added to remove the ferrous oxide, an alloy containing 60% of manganese and 15% of silicon being used. Much poor steel is made by adding too much silicon in order to speed up deoxidation and cut down the refining time. The cleanest method of deoxidation is with a carbide slag in the basic electric furnace, the reaction being :

$$3FeO + CaC_2 = CaO + 2CO + 3Fe.$$

Increased Open-Hearth Productivity. C. D. King. (Metals and Alloys, 1944, vol. 19, Apr., pp. 850–855). Methods employed at American open-hearth steel plants for increasing production are described. In furnace repairs these include the use of power-driven appliances for moving bricks, flue dust, débris and slag. Sloping back walls and basic front walls have contributed to shorten the time spent on wall repairs.

The Production of Phosphate Slags in the Pig-Iron and Ore Process. A. Rotter. (Stahl und Eisen, 1944, vol. 64, Feb. 10, pp. 90–96). As different results have been obtained in determinations of the phosphoric-acid content of slags produced by the pig-iron and ore process, an investigation of the same slags was carried out in two independent laboratories. Slag samples were prepared using a variety of ores, and the total phosphoric-acid content as well as the amount soluble in citric acid were determined. From these and other determinations diagrams were constructed showing the effect of the CaO/P_2O_5 ratio on the solubility in citric acid of the phosphoric acid in slags produced in the basic-Bessemer, Hoesch, and pig-iron and ore processes. The reduction in the value of the slag which occurs with certain ores and by reason of the lime addition can be balanced by increasing the silica by means of sand additions with suitable apparatus. The production of a high-phosphate slag takes second

place to the production of best-quality steel, so that the expedient of adding sand cannot be applied when the CaO/SiO$_2$ ratio is already low.

Metallurgical Factors Affecting the Life of Ingot Moulds. B. Körös. (Bányászati és Kohászati Lapok : Stahl und Eisen, 1944, vol. 64, Mar. 9, pp. 159–164). The factors affecting the life of ingot moulds are discussed on the basis of data reported in the literature and of experience at a Hungarian steelworks. The choice of the iron which will give the longest life is a compromise between a growth-resisting iron and a high-strength iron. The composition found to be most suitable for the steelworks in question was graphitic carbon 3·1%, combined carbon 0·5%, silicon 1·5%, manganese 0·8%, phosphorus 0·15% max., sulphur 0·1%, chromium 0·1% and copper 0·15%.

REHEATING FURNACES

Plate Mill Heating Furnaces. A. J. Fisher. (Iron and Steel Engineer, 1944, vol. 21, Apr., pp. 59 PM–66 PM). A detailed description is given of the reheating furnaces for the plate mill at the Sparrows Point plant of the Bethlehem Steel Company. There are four similar oil-fired furnaces with regenerators for preheating the air. Each furnace is 62 ft. long × 15 ft. 6 in. wide outside measurements, with a hearth measuring 40 ft. × 10 ft. The average heating rate for one furnace is 10–15 tons per hr. for 6-in. slabs charged at 1500° F. or about half this rate when the slabs are charged cold.

Metal Heating Furnaces. R. S. van der Spuy. (Journal of the South African Institution of Engineers, vol. 42, Dec. 1943/Jan. 1944, pp. 66–89). The author discusses comprehensively the problem of operating metal heating furnaces to the best advantage. The following factors are dealt with from a practical point of view : The temperature of the furnace ; handling of materials ; firing of the furnace ; the effect of the size of the charge ; heat transmission to the charge ; the furnace gases ; the effect of furnace construction ; and furnace efficiency.

FORGING, STAMPING AND DRAWING

Forging and Fabricating 1000 Pound Semi-Armor-Piercing Bomb. G. E. Stedman. (Steel Processing, 1944, vol. 30, May, pp. 285–288, 324). A description is given of the series of forging processes developed at a works in Kansas City for making large bombs out of suitable lengths of seamless manganese-steel tubing.

Forging Shot from Alloy Bar Stock. G. E. Stedman. (Steel, 1944, vol. 115, July 3, pp. 106–113). A description is given of the plant and processes at the Kansas City works of the Sheffield Steel Corporation. At this plant there are five 110-ton open-hearth furnaces working on 70% cold-metal charge and 30% hot metal supplied from two cupolas. In normal times the works produced structural steel, bolts, nuts, washers and balls for grinding mills. For war purposes part of the equipment has been changed over to the special heat treatment and forging required for making armour-piercing shells. Descriptions of the new processes are given.

Processing Steel Shells. C. W. Hinman. (Steel Processing, 1944, vol. 30, May, pp. 292–294). The design and operation of dies and punches for the mass production of steel cups with eight holes pierced through the side wall are described.

The Pressing of Sheet Metal. H. W. Swift. (Junior Institution of Engineers : Sheet Metal Industries, 1944, vol. 19, June, pp. 999–1004 ; July, pp. 1183–1188 ; Aug., pp. 1371–1374). An account is given of the pressing of sheet metal, especially the production of articles involving drawing operations. After a review of the theory and practice of press-work, separate sections of the paper are devoted to cutting operations, cupping and shallow drawing, the design of blank holders, multi-stage deep drawing, forming, and the factors which govern press capacity.

New Method Developed for Processing Wire and Strip in Molten Glass. J. J. Caugherty. (Steel, 1944, vol. 114, June 19, pp. 102–106). In the manufacture of stainless-steel wire the hot-rolled rods are pickled, fluxed, passed through a lead bath and then drawn down to the point where reannealing is necessary ; further pickling must be carried out to remove any remaining lead. A process is described which is simpler than the usual pickling, annealing and lead-removal procedure. In this the wire is first coated with lead and drawn down as far as possible ; it is then passed into a preheating furnace in which any residual lead is oxidised to lead oxide. The wire passes next into a bath of molten glass held at 1800–2400° F. The speed at which it passes through the glass is con-trolled so that a coating of the required thickness is obtained and so that the wire is annealed. The lead oxide is absorbed by the glass, which is removed after cooling, and this leaves a perfectly clean surface ready for further processing. Many economic advantages are claimed for the process.

Rod and Wire Coatings in the Cleaning House. F. M. Hauger. (Wire and Wire Products, 1944, vol. 19, June, pp. 358–361, 390). Coatings and lubricants for wire-drawing are discussed. The coating should neutralise any residual pickling acid ; it should be a good lubricant carrier and sufficiently elastic to maintain a continuous coating in the drawing operation ; and it should not be hygroscopic. The lubricant should pro-vide a strong film and not break down under the heat produced by high drawing speeds.

Modern Wire Rod Production. (Wire Industry, 1944, vol. 11, Aug., pp. 397–398). The shears and cooling banks used in modern wire rod mills have been investigated with a view to increasing output, facilitating handling and allowing the operations to be of a more versatile order than heretofore. Some modern shears, mill-train drives and annealing and hardening furnaces which achieve these objects are described.

A Multi-Die Wire-Drawing Machine of Modern Design. H. Mucke. (Stahl und Eisen, 1944, vol. 64, Feb. 3, pp. 69–75). The possibilities of increasing the drawing speed of wire-drawing machines are discussed and the designs of American and German machines are compared. A multi-die machine on which all the blocks are driven by a single motor is described.

ROLLING-MILL PRACTICE

Developments in Steel Mill Bearings. H. L. Smith. (Iron and Steel Engineer, 1944, vol. 21, June, pp. 64–65). With a view to conserving tin, lead-base bearing metals have been tried, but their properties at the temperatures experienced in rolling-mill stands are not satisfactory.

Good rolling-mill bearing metals with a lead base have been developed by additions of antimony and arsenic, the tin content being less than 1%. The method of coating the bearing shell with the alloy is described.

Bar Mill Gives to Copperweld Steel Company Greater Flexibility of Operation. C. Longenecker. (Blast Furnace and Steel Plant, 1944, vol. 32, May, pp. 547–550). A description is given of the improved rolling facilities which have been installed at the works of the Copperweld Steel Co. These include a gas-fired reheating furnace with a heating chamber 22 ft. wide and 60 ft. long, a 24-in. mill with three stands for rolling $9\frac{1}{2} \times 10$-in. blooms down to 4-in. rounds or squares, and a 21-in. mill with three stands for rolling down to $3\frac{1}{2}$-in. rounds and squares.

The Cold-Rolling of High-Tensile Strip Steels and Their Properties. A. Pomp and W. Puzicha. (Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung, 1943, vol. 26, No. 2, pp. 13–36). A report is presented on the effect of rolling at temperatures from $-183°$ C. to $+200°$ C. on the properties of steel strip. (An abridged version of this paper which appeared in Stahl und Eisen, 1943, vol. 63, Nov. 25, pp. 853–860 ; Dec. 2, pp. 880–885, has already been abstracted, *see* p. 111 A).

Bar and Tube Straightening. W. Siegerist. (Iron and Steel Engineer, 1944, vol. 21, June, pp. 35–44). The theory of the application of stresses in bar and tube straightening is explained and illustrated descriptions of many straightening machines of modern design are given.

Fundamentals of Industrial Electronics. G. M. Chute. (Steel, 1944, vol. 114, Apr. 3, pp. 112–113, 148–157 ; Apr. 10, pp. 100–101, 115, 142–148 ; Apr. 17, pp. 108–114, 144–146 ; Apr. 24, pp. 100–104, 124–130 ; May 1, pp. 120–128, 152–154 ; May 8, pp. 126–132, 163–167 ; May 15, pp. 121–126, 146–158 ; May 22, pp. 97–102, 142–144). In the first part of this series the principles of a simple form of electron valve, known as the phanotron rectifier are explained. In the second part the high-vacuum type of triode, called the pliotron, is dealt with, and it is shown how a high output can be obtained by combining a number of valves in such a way that each one of the series amplifies the output of the one behind it. In the third part a photo-electric relay and some of its applications are described. In the fourth part it is shown how electron valves can serve as alternating-current switches to close or open circuits, including large power circuits. The fifth part deals with the electronic control of heat applied by resistance welders. A high-speed photo-electric relay is described in the sixth part, and in the seventh and concluding parts the application of electronics for the stepless control of motors and for providing very high frequency current for induction heating are dealt with.

Electronics—Its Steel Plant Uses. J. H. Hopper. (Steel, 1944, vol. 115, July 10, pp. 106–108, 127). Several applications of electronic equipment in rolling-mills and other steelworks' departments are described. These include photo-electric relays for detecting pinholes in steel sheets and sheet counters.

Electronics in Review. W. D. Cockrell. (Iron Age, 1944, vol. 154, July 20, pp. 58–62). After a brief explanation of the electronic tube or valve, a number of its applications for control purposes are reviewed ; these include the control of welding, flame-cutting, machining and polishing operations.

PYROMETRY

Temperature Measurement and Control for Metallurgical Furnaces of Varying Designs. C. Sieber. (Metallwirtschaft : Sheet Metal Industries, 1944, vol. 19, May, pp. 811–812 ; June, pp. 994–996 ; July, pp. 1178–1180 ; Aug., pp. 1356–1358). The problems involved in measuring and controlling the temperature of heat-treatment and other metallurgical furnaces are discussed and the principles of various instruments for this purpose are explained.

The Direct Determination of the Rate of Temperature Change, Especially the Cooling Rate, by Electrical Differentiation of Change of Temperature with Time. W. Lueg. (Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung, 1943, vol. 26, No. 1, pp. 1–7). Tests are described which proved that the voltages and voltage changes generated by thermocouples are sufficient to enable a condenser to respond to changes of temperature and to provide a means of obtaining electrically a continuous record of the rates of temperature change in metals simultaneously with the time-temperature curve. The advantages of this method for studying the cooling rates of metals in different liquids are discussed.

A Curve Tracer with High Sensitivity and Quick Adjustment. W. Lueg. (Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung, 1943, vol. 26, No. 1, pp. 9–12). Instruments for recording changes of pressure, temperature, stress, &c., with time are well known, but graphs of the relationship between one variable and a second variable are only seldom required. In applying the apparatus for obtaining curves of the changes in the cooling rates of metals (*see* preceding abstract) it was desired to record the changes of the cooling rate with temperature. A description of a highly sensitive and rapidly adjustable optical apparatus on the principle of the Saladin recorder which was developed for this purpose is given and some examples of the curves obtained with it are reproduced.

Measurement of the Cutting Temperature by Means of Temperature-Indicating Paints. H. Schallbroch and M. Lang. (Zeitschrift des Vereines Deutscher Ingenieure, 1943, vol. 87, Jan. 9, pp. 15–19). A technique is described by means of which the temperature reached at different positions on lathe tools during turning were measured. Paints which change colour with increasing temperature were employed. A method of evaluating the results is given.

Control and Instrumentation. J. F. Black. (Canadian Society for Measurement and Control : Canadian Metals and Metallurgical Industries, 1944, vol. 7, June, pp. 38–41, 56, 57). A description is given of the temperature-measuring and fuel-control systems installed by Atlas Steels, Ltd., Welland, Ontario, for the operation of their soaking pits, continuous billet-heating furnace, heat-treatment furnaces, oil-fired car-bottom furnaces and wire-annealing furnace.

HEAT TREATMENT

Principles of Heat Treating Steel. H. L. Walker. (Illinois University, 1944, Engineering Experiment Station, Reprint Series No. 31). The iron-carbon diagram is explained, and from this starting point a comprehensive account is given of the fundamentals of the heat treatment of steel.

The S-Curve and Its Significance in the Practical Heat Treatment of Steel. A. L. Simmons. (Australasian Engineer Science Sheet, 1944, June 7, pp. 2–19). The shortcomings of the iron-carbon diagram with regard to the practical heat treatment of steel are discussed. S-curves are introduced with details of their method of construction, and their relation to cooling curves and hardenability. It is shown how variables such as composition and grain size influence the shape of the S-curves, and the modern interpretation of the martensite region is described. The continuous-cooling S-curve is dealt with briefly, and this is followed by detailed discussion of various practical treatments (such as spheroidising, annealing, normalising, austempering, " martempering " and hardening) in their relationship to the various regions in the curve. It is shown how the intelligent use of these curves enables a fairly accurate prediction to be made for designing a heat treatment to meet any normal requirement.

The Continuous Cementation of Iron Wire. (Wire Industry, 1944, vol. 11, Aug., pp. 391–393). A simple gas-carburising plant is described and the necessary modifications for the continuous gas-carburising of wire are explained. The factors which control the speed at which the wire can be passed through the furnace are : (1) The carburising temperature ; (2) the carbon content desired in the finished wire ; (3) the gauge of the wire ; (4) the initial carbon content of the wire ; and (5) the length of the furnace. These are discussed separately. Wire is generally supplied to the consumer in the annealed condition, and this obviates any post-carburising treatment other than a final pass for polishing purposes.

Heat Treating High-Speed Steels in Salt-Bath Furnaces. H. Solakian. (Steel, 1944, vol. 114, June 26, pp. 89, 111–116). The nature of the troubles commonly experienced in the high-temperature hardening of high-speed steels is briefly considered. Details on the mode of operation of the electric salt-bath furnace calculated to eliminate these troubles are given.

Redesign Increases Cyanide Pot Life. J. H. Greenberg. (Metal Progress, 1944, vol. 45, May, pp. 912–913). An account is given of the steps taken to improve the life of a 15/35 chromium-nickel steel pot for melting cyanide case-hardening salts and holding them at 1500–1600° F. The pot measured 40 × 18 × 18 in. and was heated by a single oil burner. Several changes in the metal analysis were tried without success, but a greatly improved life was obtained by changing to gas-firing, coating the outside of the pot with " Ferritrol " and constructing the flame baffles of carbon instead of fireclay refractories.

High Frequency Induction Heating. G. E. Shaad. (Iron and Steel Engineer, 1944, vol. 21, June, pp. 66–71). The principles of high-frequency induction heating are explained and the types of generator required for producing medium- and high-frequency currents for melting, for heating bars to forging heat and for the surface-hardening of bars are described.

Induction Hardening of A.P. Shot. T. E. Lloyd. (Iron Age, 1944, vol. 154, July 6, pp. 58–60). An illustrated description is given of the induction hardening equipment at the works of the Eaton Manufacturing Co., Cleveland, Ohio, which is used for the hardening of 37-mm. dia. armour-piercing shells.

Fixtures Facilitate the Use of Induction Heating. F. W. Curtis. (Machinist, 1944, vol. 88, July 29, pp. 98–100). Automatic mechanical devices to speed up the induction heating and subsequent quenching in the quantity production of small parts are described and illustrated.

Recent Developments in Utilization of Gas in Industrial Furnaces. C. Cone. (American Gas Association : Steel Processing, 1944, vol. 30, May, pp. 309–315). Progress in the preparation and use of special atmospheres for treating metals is described. The processes dealt with in-

clude : (a) The rapid cooling of hardened parts by high-velocity streams of non-oxidising gas in a chamber adjoining the heating zone ; (b) recarburising surface-decarburised parts with a special atmosphere ; (c) gas pickling ; and (d) heating furnaces with gas to a much higher temperature than that required for the parts and withdrawing the latter at the precise moment when they reach the desired temperature.

The Control of Composition and Heat Treatment in 0·25% Carbon, 1·5% Manganese Steel Castings. T. W. Ruffle. (Institute of British Foundrymen : Foundry Trade Journal, 1944, vol. 73, July 13, pp. 215–220). Data showing the variation of physical properties with the carbon and manganese contents of normalised manganese steel are given, with information on the limits of composition which can be expected to give satisfactory test results after standard heat treatment. The standard heat treatment for castings of composition within these limits is described and special treatments for castings of composition outside the selected range are mentioned.

Continuous Heat-Treating Lines. A. C. Kramer. (Steel, 1944, vol. 114, June 5, pp. 100–101, 154–156). An illustrated description is given of a continuous heat-treatment plant for armour plate, tractor links and shoes, bars and automobile parts in which the gas-fired hardening furnace, the water-spray quenching tank and tempering furnace are in one line. The plant is operated by two men and about 2½ tons of material can be treated per hr.

Rifle Parts Heat Treated in Special Furnaces. (Iron Age, 1944, vol. 153, June 15, pp. 74–78). Two automatic furnaces installed by the Lindberg Engineering Co., at Springfield, Massachussets, for the heat treatment of rifle-barrel forgings are described. A third furnace is also described below which an automatic quenching apparatus is fitted for the hardening, without distortion or scaling, of operating handles for semi-automatic rifles.

Heat Treatment in the Needle and Pin Trade. (Wire Industry, 1944, vol. 11, July, pp. 339–341). The equipment and processes for heat-treating pins and needles are described. Furnaces with either an endless belt or a sloping plate which is agitated are used. The chute at the discharge end is designed to cause the needles to enter the quenching oil vertically. The " Morax " protective atmosphere system leaves an excellent bright surface on the annealed needles ; this atmosphere is prepared by bubbling hydrogen through a volatile fluid.

Sub-Zero Temperatures for Shrink Fits. H. A. Knight. (Metals and Alloys, 1943, vol. 18, July, pp. 50–54). The advantages of cooling metal parts to temperatures as low as −120° F. as a means of fitting them into other parts so as to obtain a tight fit by the subsequent expansion are discussed and some examples involving ferrous and non-ferrous metals are described.

A Symposium on Water-Quenched Steel Castings. (Steel, 1944, vol. 114, May 22, pp. 82–88 ; May 29, pp. 86–96 ; June 5, pp. 104–110, 164–171). Six papers on the water-quenching of steel castings were recently presented at a symposium held by the Steel Founders' Society of America. In the first, C. W. Briggs reviewed the improvements which have taken place in the heat treatment of steel castings during the last 35 years. The correct procedure for water-quenching small steel castings, nickel-chromium-molybdenum steel castings in particular, was described by J. W. Juppenlatz. Practical advice on obtaining uniform heating and cooling and on the prevention of distortion was given by W. B. Libert. The equipment for heating and quenching large steel castings was discussed by R. A. Gezelius, and by R. H. Swartz in the paper which followed. Finally, the effect of the design and mass of steel castings on the dis-

tortion and physical properties obtained after quenching in water was dealt with by W. J. Phillips.

Developments in the Water-Quenching of Steel Castings. C. W. Briggs. (Steel Founders' Society of America : Foundry, 1944, vol. 72, May, pp. 58–59, 132). *See* preceding abstract.

Problems in Water-Quenching Miscellaneous Sized Steel Castings. W. B. Libert. (Steel Founders' Society of America : Foundry, 1944, vol. 72, June, pp. 130–131, 256–258). The equipment and technique for heating medium and large steel castings and then quenching them in water at an East Chicago foundry are described. Thin sections of large castings are " blocked off " with fireclay, or fireclay and asbestos, so as to reduce the cooling rate and prevent cracking when they are lowered into the water tank.

Distortion as a Production Problem. H. Petzal. (Machine Shop Magazine, 1944, vol. 5, June, pp. 80–86 ; July, pp. 72–76). The causes and cures for distortion in heat-treated parts are discussed. Normalising in the initial production stages of rods or blanks is the safest means of forestalling some of the distortion difficulties which originate in non-uniform raw material.

WELDING AND CUTTING

Ferrous Electric Welding—Fact and Fable. D. B. Johnston. (Iron and Steel Engineer, 1944, vol. 21, June, pp. 45–56). A general survey of the principles and methods of electric welding is presented, with descriptions of machines for seam-, spot-, butt- and flash-welding.

New Developments in Use of Welding in Production of Stamped Products. (Steel Processing, 1944, vol. 30, May, pp. 289–291, 296). The advantages obtained by making parts by the welding of two or more pressings are discussed and examples of parts made in this way are described.

Welding in Post-War Steel Construction. La Motte Grover. (American Institute of Steel Construction : Iron Age, 1944, vol. 153, June 15, pp. 71–73). The problems of technique, personnel and general organisation involved in the transition from a riveting to a welding practice in large ship-building and bridge-building concerns are discussed.

Gray Iron Castings Salvaged by Welding. (Foundry, 1944, vol. 72, May, pp. 116, 130). The use of the special welding rod developed by C. E. Phillips and Co., Detroit, is described in connection with the modification of a small grey-iron casting necessitated by a change in design after the casting had been poured.

Valves Repaired by Electric Welding. E. E. Kerns. (Metals and Alloys, 1943, vol. 18, July, pp. 48–49). The repair of valves for oil-refinery pipe lines by welding with 25/20 chromium-nickel steel electrodes is described.

Shrinkage Stresses in Welding. W. Spraragen and Cordovi. (Welding Journal, 1944, vol. 23, May, pp. 209-S–246-S). A comprehensive review of the American literature from January 1937 to September 1943 and of that of other countries up to January 1941 on shrinkage stresses in welding is given. A list of 124 references is appended.

A Note on the Initiation of Hardened Zone Cracks. A. H. Cottrell. (Transactions of the Institute of Welding, 1944, vol. 7, July, pp. 54–56). It has previously been found by E. C. Rollason and A. H. Cottrell (*see* Journ. I. and S.I., 1941, No. I., p. 167 A) that cracks in the base metal of a weld in high-tensile chromium-nickel-molybdenum steel are preceded

by small cracks near the weld interface. The present paper reports a few experiments performed to determine the temperature of the formation of the small cracks. The results suggest that no cracking occurs until the stage of major cracking is reached and that, once the small cracks are formed, complete failure by major cracking follows almost immediately. The whole process from the formation of microscopic cracks to the final major crack is confined to a low-temperature range which is below 100° C.

A Quantitative Study of the Stress Cycle Across Butt-Welds. K. Winterton and J. A. Wheeler. (Transactions of the Institute of Welding, 1944, vol. 7, July, pp. 56–68). A rectangular frame has been designed within which two welding plates can be rigidly restrained. The transverse stress set up when these plates are welded together has been continuously measured during and after welding by means of a mechanical extensometer mounted on one of the plates perpendicular to the direction of welding. The effect of several welding conditions was investigated by this means. Increase of plate thickness was found to be the most important factor leading to an increase in the developed transverse stress. The magnitude of the transverse stress under which failure occurred in the hardened zone of the plate was found to be surprisingly low for all welding conditions.

A Physical Examination of Welds Made from Austenitic Steel Electrodes. D. Hanson, A. H. Cottrell, K. Winterton, and P. D. Crowther. (Transactions of the Institute of Welding, 1944, vol. 7, July, pp. 44–54). Microscopic studies have been made of single-run austenitic welds in an endeavour to explain their resistance to cracking. Butt weld tests on multi-run welds gave severe interface cracking which was overcome by lining the surfaces of the welding groove with either 18/8 or 25/20 chromium-nickel weld metal. These facts were investigated by microscopic examination and mechanical tests. Austenitic steel electrodes are considered to be resistant to base-plate cracking because the hardened zone is toughened by retained austenite. Interface cracking is ascribed to the high stresses promoted by the low ductility of the multi-run 18/8 weld metal, this being due to the effects of carbide precipitation and to triaxial stresses. Cracking was successfully avoided in some ferritic steel multi-run welds by lining the welding groove with mild steel weld metal.

A Note on the Effect of Local Stresses on Mechanical Properties. A. H. Cottrell. (Transactions of the Institute of Welding, 1944, vol. 7, July, pp. 69–71). An analysis is made of the effect of local stresses existing in a material, such as those occurring in welded structures, upon the mechanical properties of that material, and it is shown that : (1) Both the observed breaking stress and the ductility may, under suitable circumstances, be reduced by the presence of local stresses ; (2) the reduction in the breaking stress is more profound the greater the intensity of the local stresses and the less the ductility ; and (3) the effect of the breaking stress, for a given local stress, is most important ; if the ductility of the material is greater than about 1%, the breaking strength value is fairly insensitive to the presence of local stresses.

The Problem of Hardened Zone Cracking. D. Hanson, A. H. Cottrell, K. Winterton and J. A. Wheeler. (Transactions of the Institute of Welding, 1944, vol. 7, July, pp. 71–74). The view is put forward that the failure of hardened zones in welding occurs under the combined influence of local stresses (the field of action of which may be limited to single martensite needles) and the main transverse welding stresses. Mutual reinforcement by stresses of these two types is only possible in materials having extremely low ductilities ; such a condition is produced in the hardened zone by overheating it during welding. On the basis of this theory a satisfactory explanation is provided of the alleviation of base-

plate cracking by preheating, delayed cooling, lining of the welding V, reduction of the carbon content of the plate metal and the use of mild steel and austenitic steel electrodes. A direct and most significant consequence of the theory is the considerable importance which attaches to the ductility of the hardened zone. Desirable plate-metal characteristics for reduced susceptibility to failure in the hardened zone are discussed.

The Influence of Hydrogen on Weldability of High-Tensile Alloy Steels. E. C. Rollason. (Transactions of the Institute of Welding, 1944, vol. 7, July, pp. 74–75). The results of tests to determine the amount of residual hydrogen in weld metal deposited by austenitic and ferritic electrodes are reported and the following explanation of the theory of the effect of hydrogen is offered : (1) Hydrogen compounds, especially combined moisture in the electrode coating, are dissociated in the arc and the atomic hydrogen is absorbed by the weld in large quantities. (2) The solubility of hydrogen is greater and the permeability less in γ-iron than in α-iron, and the permeability in both α- and γ-iron decreases very rapidly with temperature below 500° C. (3) As the steel cools, the solubility of hydrogen steadily decreases to the γ-α change point ; a sudden decrease in solubility then occurs, and if there is supersaturation, the hydrogen can either diffuse away, or at low temperatures it may be precipitated as molecular hydrogen at all discontinuities, boundaries and at cracks in martensite needles ; this produces high pressures causing triaxial stressing which is equivalent to reducing the ductility of the metal. (4) The temperature at which the γ-iron/martensite change begins is largely a function of the carbon content of the plate, whilst the alloying elements mainly affect the rate of cooling necessary to prevent decomposition of the austenite at the Ar_1 point. Carbon, hydrogen and large grain size tend to stabilise austenite. The decomposition of hydrogen-rich austenite is a function of time as well as temperature and the diffusion of hydrogen into voids also requires time ; this is why there is frequently a " period of induction " before cracking occurs.

A Suggested Cause and a General Theory for the Cracking of Alloy Steels on Welding. G. L. Hopkin. (Transactions of the Institute of Welding, 1944, vol. 7, July, pp. 76–78). This paper has been abstracted previously from Metal Treatment, 1944, vol. 11, Summer Issue, pp. 125–130 (*see* p. 129 A).

Properties of Heat-Treated Flash Welds in a Chromium-Nickel-Molybdenum Steel. J. C. Barrett. (Welding Journal, 1944, vol. 23, May, pp. 250-S–254-S). The problem of obtaining a flash-welded part which, in the heat-treated condition, has properties as good as the unwelded steel is dealt with. Flash welds were made in 1-in. rounds of a chromium-nickel-molybdenum steel. These welds were heat-treated to produce different hardnesses, and tensile tests, hardness surveys and metallographic studies were made. In the tensile tests the fractures occurred at random positions, some at the weld metal and others adjacent to the weld. When failure occurred at the weld, this was not attributable to inclusions. Changes in the direction of the flow lines caused by the upset metal might account for the lower ductility of the bars which broke at the weld.

Fatigue Strength of Fillet-Weld and Plug-Weld Connections in Steel Structural Members. W. M. Wilson, W. H. Bruckner, J. E. Duberg and H. C. Beede. (Illinois University, 1944, Engineering Experiment Station, Bulletin Series No. 350). An investigation is reported the object of which was to obtain information on the best design of fillet welds and plug welds to withstand fatigue. The first tests were planned to determine the unit fatigue strength in shear of fillet welds connecting structural plates, and the fatigue strength in tension of plates and channels connected by fillet welds. These tests indicated that the tensile-fatigue

strength of plates and channels thus connected was so much lower than the fatigue strength of the welds in shear that the tensile-fatigue of the plates or channels might govern the design of the connections for members to be subjected to pulsating or reversed loads. Of the many types of fillet-welded joint connecting plates, none had a significantly greater fatigue strength than the simple joint with longitudinal fillet welds along the sides and transverse fillet welds across the ends of the plates.

The Testing of Welds in the Laboratory and the Workshop. J. Davidson. (New Zealand Institute of Welding : Australasian Engineer Science Sheet, 1944, June 7, pp. 26–29). Welders should not only be skilful in the manipulation of their tools and the materials they are welding, but should also be conversant with the tests to which welds are subjected. For this purpose brief descriptions of the principal methods of testing are given.

Metallic Arc Welding Electrodes. H. Lawrence. (Steel, 1944, vol. 114, Mar. 20, pp. 98–101, 134–137 ; Mar. 27, pp. 98–100, 136–137 ; Apr. 3, pp. 136–140, 158 ; Apr. 10, pp. 104–106, 148–153 ; Apr. 17, pp. 106, 124, 138–142 ; Apr. 24, pp. 114, 134–144). Continuation of a series of articles (*see* p. 48 A). The properties of welds made with AWS-ASTM (American Welding Society and the American Society for Testing Materials) electrodes of the classes $E6011$, $E6012$, $E6013$, $E6020$, $E6030$, $E7010$ and E7020 are discussed.

Control of Moisture in Electrode Coatings. R. V. Anderson. (Iron Age, 1944, vol. 153, June 1, pp. 48–51). Absorption of moisture seriously affects the quality of arc welds. A procedure adopted by the California Shipbuilding Corporation for the testing of electrode-coatings for moisture content is described. A rigid system of distribution of electrodes from heated cabinets prevents deterioration of the electrodes before the welder receives them.

Industrial Application of Automatic Submerged Arc Welding. R. R. Sillifant. (Proceedings of the South Wales Institute of Engineers, 1944, vol. 60, pp. 40–56). A detailed description of the Unionmelt welding process and of its application for welding boilers and pressure vessels is given. The process has been described previously (*see* Journ. I. and S.I., 1939, No. I., p. 284 A).

Worn Parts Rebuilt by " Two-Tone " Arc Welding. J. A. Cunningham. (Iron Age, 1944, vol. 153, May 11, pp. 72–73). A rapid method of depositing metal to build up worn parts is described. A mild steel electrode is used in the holder and a high-carbon steel or cast-iron auxiliary filler rod is held to the arc. The material from the two rods is intimately mixed in the deposit and the rate of deposition is 30–50% higher than with an electrode only.

Tool Tipping by Arc Welding. G. W. Given. (Metals and Alloys, 1944, vol. 19, Apr., pp. 856–858). The technique for welding high-speed steel tips on to carbon-steel tool shanks is described. Both the tip and the shank are bevelled to take the weld metal. After tests with several kinds of welding electrode, 18/8 and 25/12 chromium-nickel steels were found to give the best results. A single bead is better than depositing two beads. After welding, the tools are ground and put into service without further heat treatment.

The Principle, Application and Development of Oxygen Cutting. R. E. Doré. (Proceedings of the South Wales Institute of Engineers, 1944, vol. 60, pp. 72–121). A comprehensive account is given of the development, present position and probable future of oxygen cutting. All aspects are dealt with including automatic profile cutting, the oxygen lance, cutting cast iron, flame deseaming, underwater cutting, and cutting with oxygen in conjunction with acetylene, propane and coal gas.

Oxyacetylene Use in the Steel Foundry. G. E. Bellew. (Foundry, 1944, vol. 72, June, pp. 120–122, 254). The use of hand- and machine-driven oxy-acetylene torches for removing sprues and risers from steel castings is described and illustrated.

Flame-Cutting in the Shipyard. G. M. Boyd. (Transactions of the Institute of Welding, 1944, vol. 7, July, pp. 79–94). A comprehensive account is given of the technique of flame-cutting as applied in ship-building with descriptions of hand and machine torches, guiding devices, profilers, tracing devices, flame planers and methods of preparing plate edges for welding. A special section deals with cutting speeds, the consumption of oxygen and fuel gas, and costs.

Plant Distribution Systems for Oxygen and Acetylene. H. Ullmer. (Iron and Steel Engineer, 1944, vol. 21, Apr., pp. 40–48). Central sources of oxygen and acetylene supply and the necessary distribution systems in iron and steel works are described. For oxygen, a large number of cylinders may be connected to a manifold, or an evaporator may be installed to receive liquid oxygen. Acetylene can also be supplied from cylinders connected to a header, or from one of two types of generator installations. One of these consists of a number of medium-pressure generators and the other of a single large-capacity generator with a gas holder and rotary compressors for maintaining the supply at the required pressure.

MACHINING

Carbide Milling of Steel. H. A. Frommelt. (Steel, 1944, vol. 114, June 12, pp. 100–104; Iron Age, 1944, vol. 153, June 22, pp. 52–57). Data on the machining of steel with milling cutters having teeth tipped with tungsten-titanium carbide are presented and discussed. These show the high cutting speeds which are obtainable using helix and rake angles which are negative in relation to the direction of rotation.

Machining Fatigue Test Pieces. H. Ford. (Machine Shop Magazine, 1944, vol. 5, Apr., pp. 44–46). Accurately curved necks were required to be turned on cylindrical specimens for fatigue-testing and the lathes available were unsuitable for this work. A description is given of a radius-turning attachment which was designed for this work and proved satisfactory when mounted on one of the lathes.

Comparative Cutting Tests of a Diamond Tool and a High-Speed Tool. M. E. Merchant. (Industrial Diamond Review, 1944, vol. 4, June, pp. 119–124). Investigations carried out by the Research Department of the Cincinnati Milling Machine Co. to find the coefficient of friction between a diamond cutting tool and the chip are described. For comparison purposes the tests were also made on a tool of 18/4/1 high-speed steel.

Controlling Machinability of Screw Machine Stock. S. B. Knutson. (Iron Age, 1944, vol. 153, June 8, pp. 62–65). The author comments on the problem of the high-speed machining of small parts of high-carbon steel. Standards of selection are drawn up based upon the " rigidity " of the steel and its degree of spheroidisation.

Statistical Methods of Quality Control. C. Stirewalt and J. Bordeaux. (Iron Age, 1944, vol. 153, May 11, pp. 56–60). Methods of using control curves plotted from statistics on the frequency with which mass-produced parts exceed their dimensional tolerances are explained with examples.

Tool Steel Coding. (Iron Age, 1944, vol. 153, Mar. 30, pp. 36–40). A description is given of the coding system employed by a firm of aircraft

manufacturers in the United States for marking tool steels. The system has the following objects : (1) To correlate the trade names of the steels with the chemical analysis ; (2) to correlate the heat-treatment practice with the specification analyses of the subject groups ; and (3) to provide a convenient code designation for each steel and thus avoid the use of trade names.

Sulphurized Cutting Oils. A. F. Brewer. (Steel, 1944, vol. 114, May 1, pp. 104–105, 141–148). The development of sulphurised machining lubricants is described and recommendations on cutting speeds, tool angles and lubricants for machining different metals and alloys are made.

Developments in Large Roll Grinding Equipment. (Sheet Metal Industries, 1944, vol. 20, Aug., pp. 1359–1361). **Modern Roll Grinding Machine.** (Iron and Coal Trades Review, 1944, vol. 148, June 2, pp. 827–828). **Roll Grinder.** (Iron and Steel, 1944, vol. 17, Aug., pp. 570–571). An illustrated description is given of a roll-grinding machine with a travelling-type wheel head. The machine is designed to accommodate rolls up to 60 in. in dia. and 24 ft. long.

PROPERTIES AND TESTS

" Strength " in Technical Parlance. A. C. Vivian. (Metallurgia, 1944, vol. 30, July, pp. 127–129). The term " strength " is used so frequently for different purposes by technical men that its meaning has become confused. It is suggested that strength might be allowed to mean the stress properties, and if so, " strength, plasticity and toughness " would then refer to the three classes of properties into which the old-fashioned concept of strength has been analysed in the last half-century. Such a use of the word satisfies the most reasonable of all the technical definitions now employed. All the stress properties, not excluding the compound properties hardness and fatigue endurance, are in fact " a material's specific reactions to deformation by force " at different stages and/or under particular conditions of loading. The easier way to describe " strength " in this sense is to represent it as the steepness and height of the stress-strain curve. According to this view, the length of the stress-strain curve represents the plasticity of the material and the area under the curve is the toughness.

The Effect of Long Annealing at Low Temperature on the Elastic Limit of Low-Carbon Steel. A. Pomp and A. Eichinger. (Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung, 1943, vol. 26, No. 4, pp. 51–58). An investigation is described the object of which was to determine how storing at room temperature and long-time annealing at 200° C. affected the appearance of Lüders lines when specimens of low-carbon steel, quenched in water from 700° C., were subjected to tensile tests. Seven steels containing from 0·02% to 0·20% of carbon were tested. Normally-annealed steel after treatment at 200° C. for 2000 hr. had a clearly defined elastic limit accompanied by Lüders lines. Quenching in water from 700° C. caused the complete disappearance of the plastic range and at the same time increased the deformation resistance. Annealing at 200° C. for only 10 hr. caused specimens tested at room temperature to exhibit a definite elastic limit accompanied by very fine Lüders lines. The difference between the elastic limits of the water-quenched normally-annealed steel with and without treatment at 200° C. for 2000 hr. was in some cases quite small although their lattice constants differed considerably. Increasing the annealing time at 200° C. caused the width of the

Lüders bands to increase, but, even after 2000 hr. treatment, they were narrower than those on the normally-annealed specimens.

The Effect of Specimen Shape on the Elongation in Tensile Testing. G. Malmberg. (Jernkontorets Annaler, 1944, vol. 128, No. 6, pp. 197– 245). (In Swedish). An investigation of the effects of changes in the length and section of tensile-test specimens is described. The elongation at fracture of cylindrical specimens is independent of the diameter provided that the ratio of the gauge length to the diameter remains constant. With rectangular specimens having a constant width/thickness ratio the elongation decreases with increasing area of the cross-section. With a constant cross-sectional area the elongation remains practically constant provided that the width/thickness ratio does not exceed 3. When this ratio increases above 3 the elongation increases, especially with short gauge lengths. When necking occurs the resulting non-uniform elongation extends along the whole specimen until it meets the restrictive influence of the specimen heads; it is therefore not possible to calculate the elongation on an arbitrary length when the elongations of two gauge lengths are known. Increasing the strain rate decreases the elongation. A very slight irregularity of the gauge-length surface lowers the elongation considerably. The restrictive effect of the specimen heads on the elongation extends for 1·5 to 3 times the diameter of the head, a fact which must be borne in mind when acceptance test conditions are changed from a high length/diameter ratio to a low one. A reduction in length takes place at the moment of fracture; this contraction is greatest near the specimen heads and increases with increasing tensile strength.

The Technical Cohesive Strength of Some Steels and Light Alloys at Low Temperatures. D. J. McAdam, jun., R. W. Mebs and W. W. Geil. (American Society for Testing Materials, June, 1944, Preprint No. 27). An investigation has been made of the technical cohesive strength of a high-carbon steel, a stainless steel, duralumin and magnesium alloys. Tension tests of notched and unnotched specimens have been made at room temperature and at selected low temperatures down to that of liquid air. Diagrams have been constructed to show the influence of notch depth, notch angle and root radius on strength and ductility. A study is thus made of the influence of the ratio of radial to axial stress on the technical cohesion limit and the influence of plastic deformation, heat treatment and temperature on the technical cohesive strength. Diagrams are also included to show the quantitative variation of strength and ductility with temperature.

The Testing of Cast Iron. K. Hoefer. (Stahl und Eisen, 1944, vol. 64, Feb. 3, pp. 76–80). Investigations of the relation between the tensile strength and the diameter of specimens of cast iron are reported and compared with the values of this ratio specified in the new German standard for bend tests on cast iron (DIN 1691).

Gray Iron—Steel Plus Graphite. J. T. MacKenzie. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1741 : Metals Technology, 1944, vol. 11, June). The properties of grey cast iron are discussed with special reference to the shape and distribution of the graphite flakes and to the findings of H. M. Howe, A. Boyles, E. Piwowarsky and A. Thum.

Cast Iron for Pressure Equipment. E. S. Clark. (Metals and Alloys, 1944, vol. 19, Apr., pp. 865–868). The microstructure and properties of cast iron suitable for containers for gases and liquids at very high pressure are discussed and some successful applications of Meehanite in this sphere are described.

Relations between the Notched Beam Impact Test and the Static Tension Test. C. W. MacGregor and J. C. Fisher. (Journal of Applied Mechanics,

1944, vol. 11, Mar., pp. A-28–A-34). Results of static tension tests on both notched and plain specimens are compared with notched-beam Charpy impact test results by using true stress-strain values. For the materials tested and under the temperature conditions imposed, it was found that the effect of the heat-treatment and testing temperatures on the energy absorbed per unit of volume was essentially the same for both the static notched-bar tension tests and notched-beam Charpy tests.

The Deformation Resistance of Cold-Worked Steel. F. Körber and A. Eichinger. (Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung, 1943, vol. 26, No. 3, pp. 37–50). Although the textures obtained by tension and compression differ, it is possible, in experiments by tension and compression, to obtain virtually the same stress-strain curve. The clearly defined elastic limit is often observed when a normally annealed low-carbon steel is stressed for the first time is probably due to the mosaic-like blocks of crystallites, but, when the upper yield point is reached, slip takes place beyond the block boundaries as if the mosaic structure no longer existed. The stress distribution over the section of cylindrical specimens will differ from the homogeneous uniaxial tensile or compressive stress according as flow begins at the surface or in the core. The resulting internal stresses have a very marked effect when the direction of stress is reversed and this is important in connection with the Bauschinger effect. A 0.2%-carbon steel after deformation was more elastically aniostropic than a 0.04%-carbon steel in conformity with the greater sensitivity to ageing of the low-carbon steel. For the same reason the quicker closing of the hysteresis loop of low-carbon steels should not be taken as proof of more rapid recovery. This in fact opposes both strengthening and ageing so that the material tends to return to the original state. This happens below the recrystallisation temperature, but with mild steel not at room temperature, however long the period.

The Behaviour of Metals Deformed by Compression. II. F. Körber, A. Eichinger and H. Möller. (Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung, 1943, vol. 26, No. 6, pp. 71–89). An investigation of the effects of previous cold-compression on the ductility of mild steel and cast steel has already been reported (*see* Journ. I. and S.I., 1942, No. I., p. 197 A). In the present paper tests are described the object of which was to study how deformation at 100°, 250°, 400°, 550° and 700° C. by longitudinal and transverse compression followed by two months ageing affected the properties of very low carbon steel. The brittleness increased with increasing deformation temperatures up to 400° C., but there was no embrittlement after compression at 700° C. It is not the deformed structure alone which is responsible for the embrittlement, but the lattice distortion, the extent of which depends on the temperature of deformation. Factors which also contribute to the embrittlement are the sensitivity to ageing which depends on the amount of aluminium added to the steel, and the weakness which develops at the grain boundaries resulting in a transverse preferred orientation after compression.

The Plastic Deformation of Metals as a Problem for Investigation. F. Körber. (Stahl und Eisen, 1944, vol. 64, Feb. 24, pp. 117–120). In the study of metals physics has been applied mainly to determine to what extent phenomena and processes conform with certain laws and has not touched very much on their characteristic properties. To fill up this gap close co-operation is required by scientific investigations and practical work, taking into account the theories developed from test results and experience. The difficulty in solving the problem of plastic deformation is due to the multiplicity of the factors involved. A suitable concept taking into account all the aspects of the deformation of metals must

be developed. Some examples are given of fundamental points requiring explanation before a solution can be found.

Characteristics of the Tuckerman Strain Gage. B. L. Wilson. (American Society for Testing Materials, June, 1944, Preprint No. 94). Investigations of the magnitude of the variation in the calibration factor of a Tuckerman strain gauge under various conditions are reported. The gauge was calibrated by means of an interferometric calibration device for five different positions, at two different temperatures, for mounting forces varying from the weight of the gauge (about 1 oz.) to 20 lb., and on materials having Vickers hardness numbers from about 10 to 800. The calibration factor was not greatly influenced by the material of the specimen provided the gauge was properly attached; it was practically independent of the position of the gauge in space and of temperature in the 70–100° F. range. By standardising the mounting force during calibration and use, errors due to variations in the mounting force could be eliminated.

Factors Affecting Hardness Relationships in the Range 50 to 250 Brinell. R. H. Heyer. (American Society for Testing Materials, June, 1944, Preprint No. 95). This paper reports on the further investigation of the relationship between Vickers and Brinell hardness test results (*see* Journ. I. and S.I., 1943, No. II., p. 166 A). Data which show the effect of work-hardening capacity and the importance of close control of the time of application of the indenter are presented and discussed. A method is described for constructing general hardness-conversion tables of improved accuracy; this is based on observation of the contour of the indentations. A testing procedure is suggested for establishing both hardness and tensile-strength conversion tables for specific materials.

The Susceptibility to Ageing of High-Tensile Structural Steels. A. Fry and L. Kirschfeld. (Zeitschrift des Vereines Deutscher Ingenieure, 1943, vol. 87, Mar. 6, pp. 123–127). An investigation of the ageing properties of high-tensile steels was carried out to determine whether they had any tendency to become brittle after plastic deformation. Basic open-hearth steels made by the normal process had a marked embrittlement tendency. Additions of more than the normal amount of aluminium to ensure thorough deoxidation reduced this tendency; normalising alone did not reduce it. The steels tested included specimens from the broken bridge over the Albert Canal in Belgium and the Zoo bridge in Berlin, and they afforded evidence of the importance of using non-ageing steels for such structures.

Investigations on the Heat of Friction and the Temperature Changes during Wear Tests. E. Siebel and R. Kobitzsch. (Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung, 1943, vol. 26, No. 7, pp. 97–106). In the first part of the paper equations are derived for calculating the heat developed by the friction of two surfaces in sliding contact. In the second part dry wear tests are described in which the temperature distribution was determined when specimens of copper, zinc and bakelite were pressed against a revolving steel ring. Rubbing speeds of over 3 m. per sec. and pressures exceeding 100 kg. per sq. cm. were used. In the copper-to-steel test the temperature steadily increased during the whole test period of 16 sec. With zinc and with bakelite maximum temperatures were reached and maintained for the remainder of the test. This was due in the case of zinc to the formation of a liquid phase, and in the case of bakelite to decomposition. Temperature measurements showed that these phenomena were confined to thin surface layers. When these stages were reached no further wear in the steel took place.

Iron-Silicon Alloys of High Initial Permeability Obtained by Special Metallurgical Treatment. F. Pawlek. (Sheet Metal Industries, 1944,

vol. 20, Aug., pp. 1347–1351). An English translation is presented of a paper which appeared in Archiv für das Eisenhüttenwesen, 1943, vol. 16, Mar., pp. 363–366.

Metallurgy and Heat Flow Problems in High-Temperature Valves. G. Gohs and W. E. Heilig. (Steel, 1944, vol. 115, July 3, pp. 90–92, 134). Experiments were made to obtain data for determining the most suitable alloy steel to use for valves in pipe lines carrying hydrocarbon gases at 1400° F. The design of the valve and thermal conductivity of the steel had to be such that the valve packing would not be heated above 750° F. After tests on 25/12 and 18/8 chromium-nickel steels, 12%-chromium steel and a cold-rolled low-carbon steel, the 25/12 steel was found to be the most suitable.

Creep Phenomena in Steel at Room Temperature. A. Pomp and A. Krisch. (Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung, 1943, vol. 26, No. 5, pp. 59–69). The results of room-temperature creep tests on six unalloyed steels, three chromium-nickel-molybdenum steels, a 14·8%-chromium steel and an 18/8 chromium-nickel steel are reported. With one of the unalloyed steels the creep fell to zero within 5 hr. (as far as could be ascertained with the apparatus used), but with the other unalloyed steels creep continued for almost 100 hr. With the low-alloy steels and one austenitic steel creep continued after several hundred hours. In some cases creep continued right up to fracture.

Study of the Effects of Variables on the Creep Resistance of Steels. H. C. Cross and W. Simmons. (American Society for Testing Materials, June, 1944, Preprint No. 25, Report of Joint Research Committee on Effect of Temperature on the Properties of Metals, pp. 3–27). The work on the creep resistance of steels previously reported by H. C. Cross and J. G. Lowther (see Journ. I. and S.I., 1941, No. I., p. 222 A) has been continued. Creep tests were made at 850° F. on a silicon-killed steel, a silicon-aluminium-killed steel, an aluminium-killed non-ageing steel, a rimmed carbon-molybdenum steel, and on plain carbon and carbon-molybdenum weld metal. All the materials were heat-treated to produce fine and coarse-grained structures for comparison of their creep resistances. Different heat treatments and cooling rates producing various grain sizes of austenite and ferrite in a 0·14%-carbon silicon-killed steel had little effect on the creep resistance, but a 0·17%-carbon silicon-aluminium-killed steel showed much better creep resistance when coarsened and cooled in air. With both steels, a heat treatment which reduced the grain size of the austenite tended to obliterate the effects of a previous coarsening treatment. Cooling in air after coarsening did not produce good creep resistance in an aluminium-killed non-ageing steel, but faster cooling in water produced a very low creep rate. The addition of molybdenum improved the creep resistance of rimming steel. Weld metal of plain carbon steel and of carbon-molybdenum steel had equal or better creep resistance than that of wrought steel of the same composition which had been heat-treated to produce the optimum creep resistance.

Correlation of Short- and Long-Time Elevated Temperature Test Methods. (American Society for Testing Materials, June, 1944, Preprint No. 25, Report of Joint Research Committee on Effect of Temperature on the Properties of Metals, pp. 28–56). A study has been made of ten types of short-time creep tests at high temperatures on a 0·35%-carbon steel and on a 0·16%-carbon steel containing 0·53% of molybdenum in order to ascertain whether they could be used to predict the long-time creep behaviour. From a quantitative standpoint the tests could not be used to predict the long-time creep strength accurately and consistently, but several tests showed sufficient promise to warrant further study. All the test methods, except the dynamic hot-hardness test,

were, however, capable of distinguishing between materials of different long-time creep strength.

Precipitation and Reversion of Graphite in Low-Carbon Low-Alloy Steel in the Temperature Range 900° to 1300° F. G. V. Smith, R. F. Miller and C. O. Tarr. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1695 : Metals Technology, 1944, vol. 11, June). The precipitation of graphite in low-carbon low-alloy steels is discussed. Previous experiments with an aluminium-killed carbon-molybdenum steel have indicated that graphitisation is accelerated by plastic deformation (*see* Journ. I. and S.I., 1943, No. I., p. 94 A). Further experiments with samples of the same steel have been carried out to find an explanation of its seemingly anomalous behaviour in that it graphitises slowly at 900–1100° F., but not at all at 1300° F. The specimens were from a high-pressure steam pipe which had failed due to precipitation of carbon after several years' service at 925° F. These were heated to 1300° F. and held at that temperature for several weeks while being protected from oxidation and decarburisation ; the graphite gradually disappeared and was replaced by carbide. It is suggested that the prevailing carbide at 1300° F., which is just under the A_1 temperature, is of the Mo_2C type and that this is more stable than Fe_3C, whereas, during long exposure at 900–1000° F., graphite forms because the prevailing carbide is then Fe_3C which is unstable and decomposes slowly. Micrographs showing different stages in the disappearance of the carbon are reproduced.

Influence of Hydrogen on Mechanical Properties of Some Low-Carbon Manganese-Iron Alloys and on Hadfield Manganese Steel. H. H. Uhlig. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1701 : Metals Technology, 1944, vol. 11, June). Experiments are reported which show the effect of hydrogen on low-carbon steels containing manganese in the 3·3–21·5% range. Both large and small specimens of the alloys with manganese in the 9–22% range became brittle on being treated with hydrogen at 1000° C. and quenched, whilst small specimens (0·160 in. in dia.) of electrolytic iron and of a 3·3%-manganese iron alloy were not embrittled, because, no matter how rapid the quench, any hydrogen dissolved at 1000° C. was not retained. The alloys treated in a vacuum at 1000° C. and quenched in a vacuum lost their hydrogen and were ductile, except those containing 6–7% of manganese. The latter were brittle because of the formation on quenching of a metastable α-phase. Tempering at 550° C. transformed the metastable or supersaturated α-phase into an α-phase at equilibrium and thus improved the ductility of the alloys, particularly those containing 3–10% of manganese.

A Test Method for the Indirect Determination of Hydrogen in Steel. H. Kjerrman. (Iron and Steel Institute, 1944, Translation Series, No. 194). An English translation is presented of a paper which appeared in Jernkontorets Annaler, 1944, vol. 128, No. 1, pp. 1–12 (*see* p. 56 A).

Investigations on the Influence of the Method of Sampling on the Nitrogen Content of Unalloyed Steels. H. Kempf and A. Neuberger. (Archiv für das Eisenhüttenwesen, 1943, vol. 17, July–Aug., pp. 5–9). It is known that steel when heated will take up nitrogen. Thus, steel at the surface of machined specimens, where it has been heated by friction, has been found to be considerably higher in nitrogen than samples from below the surface. This paper reports on investigations of the nitrogen content of basic-Bessemer mild steel, basic-Bessemer rail steel and open-hearth steel, the samples being taken from many different positions in billets and rails. The results proved that, in the drilling of samples, temperatures up to about 300° C. made practically no difference to the amount of nitrogen determined. The results were also the same whether

coarse or fine drillings were used. The procedure for nitrogen determination recommended by the Verein Deutsche Eisenhüttenleute was found satisfactory in all cases.

The Annealing of Cast Steel. A. Evers and E. Piwowarsky. (Archiv für das Eisenhüttenwesen, 1943, vol. 17, July–Aug., pp. 35–42). An investigation is described the object of which was the study of the effects of chromium and chromium plus molybdenum, the initial structure, the annealing temperature and time, and the cooling rate on the properties of cast steel. The Ac_3 point for the 0.30% carbon steel used was 850° C. The annealing temperatures selected were 820°, 850°, 880° and 910° C. with holding times of $4\frac{1}{2}$ hr., $1\frac{3}{4}$ hr. and 15 min. at each of these temperatures. The evaluation of the numerous test results showed that by careful selection of the annealing time a completely transformed structure and good mechanical properties could be obtained by annealing at temperatures slightly below or slightly above the *GOS* line ; the selection of a precise annealing temperature was not essential for obtaining the maximum impact strength, but in all cases the annealing time had to be carefully adjusted to suit the temperature selected. The optimum elongation and reduction-in-area values were generally obtained after annealing at, or slightly above, the *GOS*-line temperature. The small additions of chromium and molybdenum used (up to 0.54% of chromium and 0.30% of molybdenum) improved the impact strength and tensile strength of the steel made in the small Bessemer converter but did not affect the strength of the open-hearth and electric-furnace steel. The impact strength, elastic limit and tensile strength were lower after cooling in the furnace than after cooling in air.

The Impact Toughness of Cast Steel. A. Evers and E. Piwowarsky. (Stahl und Eisen, 1944, vol. 64, Mar. 2, pp. 142–144). The effect of different annealing conditions on the properties of chromium- and chromium-molybdenum cast steels has already been reported (*see* preceding abstract). In the present paper the impact-test results on these steels are evaluated by means of three-dimensional diagrams which show the relation between annealing time, annealing temperature and impact strength. Steels made by the basic-Bessemer, basic open-hearth, acid open-hearth and electric-furnace processes were tested. Bessemer steel had the lowest impact strength and was least affected by the annealing conditions. Basic open-hearth steel was most susceptible to the annealing conditions, whilst acid open-hearth and basic electric-furnace steels exhibited medium impact strength and were only affected to a moderate extent by the annealing conditions.

Effect of Phosphorus and of Various Alloying Elements on the Temper Brittleness and Heat Embrittlement of Structural Steel. E. Maurer, O. H. Wilms and H. Kiessler. (Iron and Steel Institute, 1944, Translation Series, No. 185). An English translation is presented of a paper which appeared in Stahl und Eisen, 1942, vol. 62, Jan. 29, pp. 81–89 ; Feb. 5, pp. 115–116 (*see* Journ. I. and S.I., 1942, No. II., p. 32 A).

Boron in N.E. 9440 and S.A.E. 4640 Steel. G. F. Comstock. (Iron Age, 1944, vol. 154, July 13, pp. 48–53). Further investigations of the properties of steels treated with boron are reported (*see* Journ. I. and S.I., 1944, No. I., p. 63 A). In the present paper the results of tests on 0.40%-carbon steels and on steels alloyed with chromium, nickel and molybdenum with and without additions of 0.08% of titanium and 0.005% of boron are given. The boron-treated unalloyed steels were equal to the alloy steels without boron in their tensile, impact and machining properties and were equal and sometimes superior to them in hardenability.

Substitute High Speed Steel. A. Linley. (Journal of the Birmingham Metallurgical Society, 1944, vol. 24, Mar., pp. 3–18). The development

in the use of molybdenum as a substitute for tungsten in high-speed steels is reviewed with special reference to the 6/6 and 4/6 molybdenum-tungsten steels. When certain hardening temperatures are exceeded, the material as heat-treated is softer than when treated at lower temperatures. In the case of 18/4/1 tungsten-chromium-vanadium steel, maximum hardness is produced by quenching from 1250–1270° C., whereas for the above 4/6 steel the optimum temperature is 1200–1230° C. Similarly, the tempering temperature of the latter steel is lower than that of the former (550° and 600° C. respectively). The 4/6 and 6/6 steels are far more suspectible to grain growth at high hardening temperatures than 18/4/1 steel, so that they should be removed from the furnace as soon as they have attained the required temperature throughout.

Experience with Ribbed Reinforcing Bars for Concrete. E. Reinius. (Teknisk Tidskrift, 1944, vol. 74, July 29, pp. 897–901). (In Swedish). The properties of ribbed steel bars for reinforcing concrete are discussed and their advantages as compared with plain bars are pointed out.

Aircraft Requirements of Steel Castings. V. N. Krivobok. (Metal Progress, 1944, vol. 45, May, pp. 889–891). Some problems encountered in having steel castings accepted as satisfactory for aeroplane construction are discussed. Parts might be cast oversize and then forged to the dimensions required, thus securing the advantages of forged material at the surface.

The Occurrence, Testing, Cause and Elimination of Rail-Foot Cracks. R. Kühnel. (Stahl und Eisen, 1944, vol. 64, Mar. 16, pp. 169–175; Mar. 23, pp. 187–194). The occurrence of cracks at the foot of flat-bottomed rails supplied to the German State Railways was sufficiently frequent to justify setting up a committee to investigate the cause. A statistical investigation dividing the rail failures according to the year of delivery, the manufacturing works and type of track was carried out; static and dynamic bend tests and the magnetic powder method of crack detection were also employed on new and old rails. The surface condition of the rail foot was not uniform, different conditions of crystallisation being observed at random positions, but these irregularities led to cracks only when they were aggravated by some other condition such as that resulting from cold-straightening. On the whole, basic-Bessemer and open-hearth steel rails showed no appreciable difference.

Tenth Progress Report of the Joint Investigation of Fissures in Railroad Rails. R. E. Cramer and R. S. Jensen. (Illinois University, 1944, Engineering Experiment Station, Reprint Series No. 28). The results of tests carried out since the Ninth Progress Report was issued (*see* Journ. I. and S.I., 1944, No. II:, p. 24 A) are presented in the form of three short papers as follows :

> **Field Tests for Batter of End-Hardened Rails in Service on the Chesapeake and Ohio Railway.** R. S. Jensen.
> **Examination of Carey End-Hardened Rails for Weeping Cracks.** R. E. Cramer.
> **Examination of Control Cooled and Brunorized Rails which Failed in Service.** R. E. Cramer.

Second Progress Report of the Investigation of Shelly Spots in Railroad Rails. R. E. Cramer. (Illinois University, 1944, Engineering Experiment Station, Reprint Series No. 29). Laboratory studies of the causes of horizontal cracks tending to result in shelling or flaking of the surface of rails are reported. The rolling-load testing machine designed to produce shelling is described.

Second Progress Report of the Investigation of Fatigue Failures in Rail Joint Bars. N. J. Alleman. (Illinois University, 1944, Engineering

Experiment Station, Reprint Series No. 30). Since the issue of the First Report on Rolling-Load Tests of Joint Bars (*see* Journ. I. and S.I., 1944, No. II., p. 24 A), eleven more tests have been completed the results of which are given in the present report. It was found that with the standard wheel load of 44,400 lb. and a bolt tension of 5000 lb. the life of the joint bars was very much greater than when the bolt tension was either 15,000 or 35,000 lb.

METALLOGRAPHY AND CONSTITUTION

Canada's New Physical Metallurgy Research Laboratories. (Canadian Mining and Metallurgical Bulletin, 1944, July, No. 387, pp. 302–324). A description is given of the physical metallurgy research laboratories recently completed at Ottawa for the Department of Mines and Resources. Some of the projects for the development of better war equipment and the improvement of industrial processes which are being carried out are described in general terms.

Electrical Devices Applied to Metallurgical Research. E. V. Potter. (United States Bureau of Mines, 1944, Technical Paper No. 661). Some applications of electronic devices in metallurgical research are described with illustrations and wiring diagrams. The present paper deals with unusual applications in the fields of temperature measurement, length and displacement measurements, damping capacity, production of sonic waves, magnetic testing, induction furnaces, and chemical and spectrographic analyses.

The Micro-Topography of Finely-Finished Reflecting Surfaces. J. F. Kayser. (Machinery, 1944, vol. 65, July 27, pp. 85–89). A method for quantitatively determining the micro-topography of finely finished reflecting surfaces on which the maximum depth of the surface imperfections are of the order of 1 micron is described. The method is based on the measurement of the distance between interference fringes seen in a microscope when the surface in question is viewed through a glass or diamond slip resting on the surface at an angle of about 1° to it.

Electrolytic Methods of Polishing Metals. S. Wernick. (Sheet Metal Industries, 1944, vol. 19, Apr., pp. 613–616; June, pp. 979–985; July, pp. 1172–1177). In the first part of this paper the theory and the history of the electrolytic process of polishing metals is described. In Part II. electrolytic methods of polishing stainless steels are described with special reference to Uhlig's process based on phosphoric acid and to other processes with the sulphuric-acid type of electrolyte. In Part III. methods of producing bright nickel coatings with a separate polishing process, and the electrolytic polishing of dull nickel coatings are discussed. Details are given of solutions based on sulphonic acids (*e.g.*, the Schlötter electrolyte) and of cobalt-nickel baths due to Hinrichsen and to Weisberg and Stoddard.

Some Applications of X-Rays in Engineering. L. Mullins. (Engineering Inspection, 1944, vol. 9, Summer Issue, pp. 11–22). A comprehensive account of the principles employed in the production and application of X-rays for engineering purposes is given. The technique employed in the radiographic inspection of welds and castings and examples of engineering applications of X-ray crystal analysis are described.

Radiography Applied to Welding. L. W. Ball. (American Welding Society : Iron Age, 1944, vol. 153, May 25, pp. 54–58). The theoretical basis of X-ray photography applied to the investigation of the quality of

welds is briefly considered. The means of interpreting X-ray photographs of welded joints is described. A million-volt X-ray equipment designed for the General Electric Company and a mobile X-ray unit are described. The need is emphasised for co-operation between the welding engineer and the radiographer so that standards of acceptability of welded products can be set up.

Metallurgy of the Gray Iron Matrix. R. J. Hafsten. (Iron Age, 1944, vol. 153, June 22, pp. 48–51). Isothermal transformation curves for grey cast iron are considered and compared with similar curves for steel. The austenite in the matrix of heated cast iron varies in its transformation rate at different temperatures below the critical point, and it is this variation that determines the characteristics of the S-curve and the physical properties of the matrix in the as-cast or heat-treated condition. The chemical composition of the iron and the grain size of the austenite are the main factors influencing the shape and position of the S-curve and the response of the austenite to a given heat treatment.

The Bainite Reaction in Hypoeutectoid Steels. E. P. Klier and T. Lyman. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1696 : Metals Technology, 1944, vol. 11, June). The isothermal decomposition of austenite has been studied in plain carbon steels containing 0.22%, 0.36% and 0.47% of carbon and in hypoeutectoid steels containing chromium, chromium and molybdenum, uranium, nickel, manganese and copper in solution. The isothermal transformation diagrams are presented in the approximate order of decreasing separation in time of the bainite and pearlite reactions. The following mechanism of the formation of bainite in hypoeutectoid steels is proposed : (1) In restricted volumes, rapid movement of the carbon takes place in such a way as to yield austenite regions of alternate high and low carbon concentration ; (2) the low-carbon austenite transforms at the reaction temperature into a supersaturated ferrite by a martensite-like lattice rearrangement the degree of supersaturation of the product being a function of temperature ; and (3) this supersaturated ferrite at once begins to decompose, precipitating an iron carbide in a ferrite matrix to form the dark-etching acicular product known as bainite.

CORROSION OF IRON AND STEEL

A Study of the Surface Film on Chromium-Nickel (18/8) Stainless Steel. W. H. J. Vernon, F. Wormwell and T. J. Nurse. (Iron and Steel Institute, 1944, this Journal, Section I). The surface film was stripped from chromium-nickel (18/8) austenitic stainless steel and metals present were determined by chemical analysis ; the contents of the corresponding oxides were computed. The thickness of the film as measured by total oxides present (Cr_2O_3, Fe_2O_3, NiO) increases with the degree of polish. There is a marked enrichment of chromium in the film as compared with the underlying steel, and this enrichment also increases with the degree of polish. Films from brightly-polished specimens contain about 90% of chromic oxide, the balance being mostly ferric oxide. No enrichment of nickel has been observed. The use of chromic oxide as a final polishing material does not appreciably affect the content of chromic oxide in the film. When alumina is used for the final polishing this substance is introduced into the film and the concentration of chromic oxide is simultaneously reduced. Electrode potential measurements on specimens immersed in $N/200$ sodium chloride solution have confirmed that polishing

with alumina yields a less passive surface than polishing with chromic oxide; also that a surface from which the film has been removed is considerably less passive than the polished surface. It is suggested that enrichment of chromium (as chromic oxide) in the film is associated with surface flow, the rate of oxidation being controlled partly by the free energies of formation of the respective oxides, and probably to a greater extent by selective oxidation arising from the restriction of oxygen at the interface between the metal and polishing material.

ANALYSIS

(Continued from pp. 116 A–117 A)

The Routine Spectro-Chemical Analysis of Steel. L. G. Young. (Engineer, 1944, vol. 178, Aug. 18, pp. 116–118). It has been shown by F. G. Barker that the presence of segregates in steel was liable to influence the accuracy of analyses obtained by spectro-chemical methods unless suitable precautions were taken (*see* Journ. I. and S.I., 1939, No. I., p. 211 P). Investigations have since been made in the Bragg laboratories and a technique has been developed by which a single spectrogram is obtained from six superimposed exposures at different positions on the prepared surface of the sample. Details of this technique are given with descriptions of some of the special equipment employed which includes a 15-micron fixed slit, a device for taking up wear on the arc and spark stands and a cutter for graphite electrodes.

Organic Reagents in Quantitative Metallurgical Micro-Analysis. R. Belcher and C. E. Spooner. (Metallurgia, 1944, vol. 29, Apr., pp. 329–332; vol. 30, May, pp. 49–52). The theory underlying the application of organic reagents to micro-metallurgical analysis is summarised with particular reference to compounds in which some of the principles of complex formation are indicated. Some more recent practical methods by which these compounds have been utilised in microdeterminations of metals are described.

Micro-Electrolytic Methods of Chemical Analysis. H. J. S. Sand. (Metallurgia, 1944, vol. 30, June, pp. 107–110). The development of electrolytic methods in gravimetric determinations of minute amounts of metals is described.

Analysis by Internal Electrolysis—A Semi-Micro Method. J. G. Fife. (Metallurgia, 1944, vol. 30, July, pp. 167–169). One development of electrolytic methods of micro-analysis is that which does not require the application of a current from an outside source. By this method, known as internal electrolysis, as little as 0·5 mg. of a more noble metal, *e.g.*, copper, can be quantitatively determined in the presence of 5 g. of a less noble metal, *e.g.*, iron or zinc. The principles of the method are explained with a description of the apparatus used.

Microchemistry and Its Borderline : The Instrument as an Analytical Tool. D. L. Masters. (Metallurgia, 1944, vol. 30, July, pp. 169–170). The various methods of microchemical analysis have become so specialised that no one firm undertaking analytical work could hope to acquire all the necessary apparatus for the application of all the methods ; there is therefore room for consultants or consultant bodies whose function it would be to examine analytical problems and direct them to the particular specialist whose method of analysis is the one most likely to provide the solution.

Rapid Nickel Determination. H. L. Mauzy and H. Yellin. (Metal Progress, 1944, vol. 45, Apr., pp. 689–690). A rapid method for the

colorimetric determination of nickel in commercial steels is described. The method is based upon the observation that dimethylglyoxime reacts with nickel in an alkaline solution to give, in the presence of a strong oxidising agent, a wine-red solution that obeys the Lambert-Beer law.

Colorimetric Determination of Nickel in Steel. C. G. Hummon. (Steel, 1944, vol. 114, June 19, p. 97). Details of a colorimetric method for the rapid and accurate determination of nickel in steel are given. The method is based on the reaction of dimethylglyoxime and is similar to that described by Mauzy and Yellin (*see* preceding abstract).

The Determination of Sulphur in Cast Iron by the Combustion Method. W. J. Roskrow. (Foundry Trade Journal, 1944, vol. 73, July 6, p. 198). A combustion method for the determination of sulphur in cast iron is described. A 1-g. sample in a boat is heated in a Silit-rod furnace to 1300–1350° C. (in the case of high-duty alloy cast iron) and oxygen is passed over it. The gases pass through burnt asbestos wool and dry cotton wool into a vessel containing $N/50$ AgNO$_3$ solution. The silver nitrate solution assumes a red tinge. After a short period it is titrated with $N/200$ sodium hydroxide and the amount of the latter solution required is a direct measure of the sulphur content of the sample.

Determination of Germanium in Steel. A. Weissler. (Industrial and Engineering Chemistry, Analytical Edition, 1944, vol. 16, May, pp. 311–313). A gravimetric method for the determination of germanium in steel is described. The error is of the order of 0·001% per 0·5% of germanium and the method is applicable to steels containing up to 0·5% of germanium.

Fundamentals of Coal Sampling. B. A. Landry. (United States Bureau of Mines, 1944, Bulletin No. 454). The purpose of this bulletin is to furnish another contribution to the growing list of studies on the principles governing the establishment of specifications for the sampling of coal. The field covered can be seen from the following chapter headings : (1) Variability of ash content of coal ; (2) theory of random sampling ; (3) sampling characteristics of a coal in pieces of equal weight ; (4) sampling characteristics of a multiple-size coal ; (5) relation of variability of ash of coal pieces to their weight and to their ash content ; (6) theory of orderly sampling ; and (7) coal-sampling specifications.

Sampling and Analysis of Coal and Coke for Performance and Efficiency Tests on Industrial Plant. (British Standards Institution, 1944, No. 735).

Determination of Magnesia in Magnesite and Dolomite. A. J. Boyle, C. C. Castro and R. M. Haney. (Industrial and Engineering Chemistry, Analytical Edition, 1944, vol. 16, May, pp. 313–314). The estimation of magnesia in magnesite and dolomite by potentiometric titration is described. A procedure is given which eliminates the interference of weak bases such as ferric iron, aluminium and titanium. The method is accurate and rapid.

SUBJECT INDEX.

[References to the papers read before the Institute are indicated by the word *Paper* following the page number. The letter *P.* denotes a reference in Section I. of the Journal which contains the reports of the proceedings of meetings, the papers read, and the discussions thereon. The letter *A.* denotes a reference to the section dealing with abstracts.

Indexing of Alloy Steels and Other Alloys. In the indexing of alloy steels, carbon and iron are ignored and the alloying elements contained in the steel are arranged in alphabetical order; for example, all references to nickel-chromium-molybdenum steel will be found under the heading chromium-molybdenum-nickel steel. In the indexing of other alloys, carbon and iron, when present, are included in the title; iron, when present, is always mentioned first and the other elements follow in alphabetical order, carbon being in all cases mentioned last. Examples: " Iron-silicon-carbon alloys " and " iron-chromium-nickel-carbon alloys."]

NAME INDEX.